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Applying Technology to Train Visualization Skills

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SDS International, Inc.

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14. ABSTRACT *(Maximum 200 words)*
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Training visualization skills, such as terrain appreciation, is generally difficult and inefficient in the real world with natural representations or in a classroom with analog representations. Field training requires physical relocation of trainees to multiple sites and is constrained by the terrain types and features at the physical sites available. Classroom training is traditionally based on analog methods with inflexible formats (e.g., graphics and pictures) that afford little control over viewing perspective, environmental conditions, or comparison with map representations. In contrast, the application of digital methods to train and enhance visualization skills may overcome many of these training limitations. This Phase I effort addressed three objectives: identify a set of key visualization skills required by warfighters, develop core technologies for training those visualization skills, and develop digital training methods based on the core technologies. In particular, the training approach dynamically varies digital terrain representations to match real world perspectives and attempts to foster cognitive engagement by providing trainees direct control over the matching process (e.g., morphing between 2-dimensional and 3-dimensional terrain perspectives).

15. Key Words
STTR Report   Pattern Recognition   Training   Human Performance   Perception   Visualization

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APPLYING TECHNOLOGY TO TRAIN VISUALIZATION SKILLS

EXECUTIVE SUMMARY

Research Requirement:

Skilled pattern recognition characterizes expert performance, but the training to develop such expertise is often unavailable, inefficient, and ineffective. The lack of formal training in terrain visualization, for example, may reflect the difficulty and inefficiency of conducting such training in either the real world with natural representations or in a classroom with analog representations. Training in the field requires physical relocation of trainees to multiple sites and is limited to the types of terrain features and patterns available at those sites. Classroom training is often limited to analog methods, such as drawings or photographs, which provide little or no control over viewing perspective, visibility conditions, or comparison with 2-dimensional (2D) maps.

When pattern recognition is trained, the methods require regimented conditions that pair task stimuli and responses consistently and then ensure that the responses are followed by immediate feedback over numerous learning trials. The complexities of the real world, however, often lack similarly structured conditions and feedback resources for learning to recognize patterns. The current research examines how digital training methods might overcome the limitations in training pattern recognition, such as terrain visualization. The research will apply digital training methods to control training sequence, maximize trial iteration, ensure task conditions are consistent and manageable, and provide accurate and immediate feedback on response errors. In addition, the training methods will attempt to make the process required to recognize important patterns and situations in our environment more visible and engaging to the trainee. To meet the requirement for training to provide visualization skills, a Phase I U.S. Army Small Business Technology Transfer Research (STTR) contract was awarded to SDS International, Inc. and Tuskegee University.

Procedure:

The research addressed the following objectives: identify a set of key visualization skills required by warfighters, develop core technologies for training those visualization skills, and develop digital training methods based on the core technologies. First, a set of common battlefield scenarios were developed and reviewed by military subject matter experts from the U.S. Marine Corps Reserve. Their review identified important visualization skills used by warfighters at critical junctures of the scenarios as well as the likely actions and responses of warfighters to the situations. Second, SDS conducted a review of core technologies and supporting infrastructures for training visualization skills such as terrain visualization. Key technical considerations included training effectiveness, training development efficiency, and training delivery cost and availability. Common features available from advanced training tools were identified to guide architectural choices and influence design decisions. Third, Tuskegee University conducted a review of training methods and in particular methods for training the recognition of patterns and situations in support of human visualization. The review stressed the

matching of training theory with the capabilities of technology to maximize learning. Based on the visualizations required and the training methods identified, SDS modified the core technologies available to develop a working set of prototype demonstrations for training human visualization skills.

Findings:

The review by military subject matter experts identified and selected a small set of 10 distinct visualization skills required for the battlefield scenarios examined. Examples of the visualization skills identified included: 2D to 3D terrain correlation, line-of-sight, and dispersion estimation. To better relate the small set of skills identified to the larger domain of required warfighter visualizations, each of the selected skills was associated with one of the following military factors: *mission, enemy, terrain, troops, and time* (METT-T). The selected skills also guided the review of technologies and training methods. Feasibility assessments indicated that SDS' current set of visual tools provided a powerful basis for developing visualization training. However, tool refinements were needed to adequately address the specific visualization skills selected. The refinements supported the development of working demonstrations of how the technology might be used to train and enhance each of the ten visualization skills identified. The demonstrations also helped the researchers examine the feasibility of the methods proposed within the time, scope, and cost of a Phase II STTR effort. Findings also include the development of draft training plans and outlines by Tuskegee University for a majority of the visualization skills identified. The plans apply digital training methods to control training conditions and provide feedback. The plans also include a training approach that dynamically varies digital terrain representations to match real world perspectives and attempts to foster cognitive engagement by providing trainees direct control over the matching process (e.g., morphing between 2D and 3D terrain perspectives).

Utilization of Findings:

The research objective is to use the results from this Phase I STTR for Phase II development and refinement of innovative digital training methods to help warfighters visualize the battlefield. The research focus on useful solutions emphasizes that the methods developed must result in an affordable, robust, and highly portable distributed training system. The training design also stresses a scalable technical architecture for rapid modification of the training to match the rapid emergence of visualization requirements in the varying contemporary operating environment.

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Introduction

During Phase I of this STTR, SDS International, Inc. (SDS) directed its efforts to meet three primary objectives. The first was to study a number of common battlefield scenarios and leverage the experience of subject matter experts to identify the salient set of visualization skills needed by the warfighters in those scenarios to enhance their effectiveness and survivability. The second was to research the technologies that could be harnessed to create feasible methods for training the identified visualization skills, and wherever possible, to demonstrate proof of concept using suitable prototypes. The third and final objective was to establish a robust training process for each visualization skill with assistance from Tuskegee University. Each process was required to be coordinated with the corresponding technology and vice-versa, and had to be capable of providing measurable results during training.

Approach

In the following subsections, we describe in greater detail the scenarios that were used to derive the various visualization skills, the set of requirements used to define the technologies proposed for training those skills and a broad set of guidelines to define the training processes.

Identification of Visualization Skills From Scenarios

To identify the visualizing skills critical to success on the battlefield it is necessary to recognize the domain of operations on the battlefield that require those skills, and the context in which such skills are put to use. For this purpose, we take a look at the operational roles of warfighters at various tiers of an organized force in two holistic examples characterizing battlefield dynamics. In each example we highlight using italicization, the important visualization skills performed by various warfighters in their respective scenarios as identified by subject matter experts. The two following scenarios yield a reasonably extensive set of visualization skills for which suitable training tools and processes can be developed within the scope of this project.

Scenario 1

Consider a scenario involving a mechanized rifle company operating in an insecure mountainous region of a nation at war. The company is assigned the task of proceeding to a designated area at a distance of 10 miles from their current holding position using a specified route plotted on a (orthographic-view) contour map. The area has been chosen because of a variety of factors. It is located on high ground and the approaches to the area have very few natural formations – other than a few small hills – that can offer protection to an advancing enemy force. Upon arriving at that area, three platoons within the company are to secure the area by establishing defensive positions while elements of the remaining company scout the surrounding area for enemy activity.

Before proceeding to its destination, the company must be thoroughly familiar with its route to ensure that it remains true to its assigned course. An effective way to achieve this is by ensuring that at least the drivers and navigators in the company readily recognize landmarks and

use them to validate their position at any given time during their journey. This requires the company to be *able to correlate the features of the terrain on the contour map on which their route has been described with its corresponding 3 dimensional (3D) topography.*

Upon arriving at their destination, the commander of the platoon that is assigned the task of reconnoitering the surrounding area draws up the route to be followed for scouting on a contour map. Such a path should be plotted with a focus towards achieving two objectives. First, the area of the surrounding terrain having line-of-sight (LOS) to that path should be maximized to ensure that the fewest number of areas remain out of sight where enemy forces can remain hidden. Second, the cost of traversing the plotted path should be as low as possible to ensure that the process of reconnoitering is completed in the least possible time. The former objective requires the scouts to be *able to visualize the LOS to the terrain surrounding the points on a path*, while the latter requires them to be *able to visualize and qualitatively estimate the relative ease or difficulty of traversing terrain using a given path.* Again, while proceeding along their assigned paths, the scouts have to be cognizant of their surrounding topography and landmarks.

In the meantime, the three platoons assigned the task of establishing defensive positions must set up a perimeter with lookouts situated at vantage points that afford LOS to the maximum possible area of the surrounding terrain. These lookouts must not only be adept at detecting an approaching force but also be capable of ascertaining with some confidence its constitution in terms of numbers. To accomplish this, they must be able to interpret and visualize the nature of a potential threat from its signature. Signatures include details such as dust trails generated by entities or the smoke emitted by engines.

Meanwhile, each squad sets up its heavy machine gun and individual riflemen survey the various approaches to their positions. Although laser range finders are available to general infantry, its use during the heat of battle impedes the generation of the desired volume of fire that may be required to thwart a determined enemy advance. Hence, to ensure that their marksmanship is not compromised (nor ammunition wasted), individual riflemen must be able to estimate distances along each approach towards which their weapons are trained.

Suppose, that after some point in time, the scouts spot an enemy column moving towards the entrenched position of its company. They must relay this information back to their company and also call up supporting arms (e.g., air or artillery) to neutralize the enemy column. Let us assume that artillery support does not have the requisite range to support the scouts and that calling for air support is the only viable option. The items of information that must be conveyed to the pilots of the supporting aircraft are the coordinates of the enemy column on the contour map in addition to the spread of the enemy formation. For estimating the latter, a scout must be able to estimate the dispersion of the enemy force.

However, also suppose that the enemy column is moving rapidly and is likely to engage the main body of the company at close quarters before air support can arrive and be used. To be able to ascertain this, the scouts must be able to visualize dynamics with respect to time. The scouts withdraw back to the entrenched positions established by their company and provide the company commander an Estimated Time of Arrival (ETA) of the enemy column. As the enemy

column appears within the visual range of the company, its commander and his subordinates quickly identify the most immediate set of threats that have to be neutralized. To achieve this, the commander and his subordinates must be able to visualize and prioritize the threats. Also, the company commander instructs the mortar crew to lay down a steady rate of fire – of approximately a round every 3 seconds – on the approach being taken by the entities posing the highest level of threat. Furthermore, the company commander determines that, to prevent the enemy from seeking cover behind the few small hills on the approaches to their position, the mortar crew must be able to retrain their weapons on to those hills and force the enemy to keep advancing (and accept high losses) or retreat. However, to achieve this goal, the company commander must be capable of visualizing trajectory and estimating future positions of the aforementioned threats to ensure that his command to divert fire on to the desired hills is warranted.

In Scenario 1, at least nine different visualization skills are applied by various members of the company at different levels in its hierarchy to enhance their effectiveness and survivability as a force. The report discusses and illustrates the technologies that might be used to train all these skills.

Scenario 2

Consider a scenario involving an Unmanned Aerial Vehicle (UAV), such as the Global Hawk, investigating enemy activity over a large swathe of terrain from a high altitude, say 30,000 ft. The UAV has a real-time feed, using which the operator navigates the vehicle and also surveys the terrain beneath it using electro-optical, infrared, or synthetic aperture radar systems. The reconnaissance operation is to provide advance warning of the enemy's intent to a regiment manning a defensive front spanning over 30 miles that faces the enemy. The regiment commander understands that the strength of the regiment is insufficient to establish fixed defensive positions against sizeable enemy advances, say one or more regiments. That would spread the defense too thinly, and would likely result in the enemy breaching through wherever they might choose to focus their thrust. Therefore, the defense has to employ a high degree of mobility and ensure that the significant points of the enemy's thrusts are met with suitable numbers of its own force and supporting arms.

Suppose that, during this reconnaissance operation, the operator detects a fairly large number of enemy entities, say over one regiment at a distance of over 150 miles from the defensive front. The position of the UAV is known to its operator at every instance and, therefore, by transitivity, the positions of the entities seen by it are also known within an extremely small margin of error.

Personnel on the ground view successive frames of images captured by the UAV of the enemy below in real-time. The positions of the entities appear to change over time indicating motion, but the clutter produced by the large number of entities in close proximity to each other requires very close attention to discern between the significant units comprising the enemy force and where each unit is headed. Such information is vital for the regiment commander to be able to decide how to reorganize and commit his own forces. For this purpose, the photo/image interpreters on the ground must be able to visualize formations and their likely heading.

Furthermore to estimate the ETA of the various enemy formations, the regiment commander must also be able to visualize dynamics with respect to time based on the visualized trajectory of those formations.

In contrast to Scenario 1, Scenario 2 is more strategic in nature and demonstrates how the regiment commander uses at least two visualization skills to enhance the effectiveness and survivability of his force. There are numerous other scenarios that may be studied to extract a core set of visualization skills that are frequently required and used by the warfighter.

Requirements for the Technologies and Infrastructure for Training

Contemporary training systems and their supporting infrastructure are increasingly pressed to meet a common set of requirements to enable the training process to be conducted efficiently and economically. The technologies for training resulting from SDS' research in this phase must afford integration into training tools that adhere to the following set of requirements.

a. All training modules and systems should be configurable with minimal manual effort. For example, the methods and steps necessary to load a scenario defining a terrain database on which an exercise is to be conducted and the sequence of actions of the entities participating in it must be intuitive and uninvolved.

b.. The methods for the management of multiple training systems should be available through a single administrative interface. Thus, a single administrative station should furnish the capabilities to permit an instructor to manage the exercises on multiple student stations and instruct students dynamically on details that are relevant to their training.

c. The training systems should be capable of being geographically distributed. Generally they should provide suitable network interfaces and methods to permit them to be used in a long-haul network that is insensitive to the geographical location of the students and the instructor.

d. A distributed training system must provide suitable methods for high quality communication and information distribution in real-time, in the absence of which the quality of training and the subsequent performance of the trainees is likely to experience attenuation (Jentsch, et al., 1995). Thus the training infrastructure should incorporate such facilities that enable geographically dispersed trainees and instructors to visually and audibly interact with each other.

e. The hardware comprising the training systems and supporting infrastructure must be portable to enable the system to be quickly deployed in the field and to be ported from one site to another with the least cost of labor. However, such portability should not be availed at the expense of functional value or the quality of training.

f. The training system and its supporting infrastructure should be realized using Commercial-off-the-Shelf (COTS) hardware to ensure the cost effectiveness of commercialized systems and the ability to obtain vendor-independent support, replacement or upgrades to hardware.

SDS International's visualization tools comprised of the SDS AAcuity® Personal Computer-Image Generator (PC-IG) and improved Spectator/NEXWARS Viewer (referred to as NEXWARS) and their system infrastructure adheres to all the aforesaid requirements. They are designed with a focus on enhancing the quality of interactive training in a distributed environment using economical vendor-independent hardware. Furthermore, NEXWARS provides all the necessary functionalities for the management and coordination of such training sessions and all necessary interactions between instructor and trainees.

The visualization skills that have been identified in this report are applicable to the domain of trainees at various levels in the hierarchical structure of a force. Some skills are crucial to the tactical efficiency of a warfighter at the lowest tier of operations within a heterogeneous force, while others have direct relevance to the effectiveness of the force itself. The skills involve the visualization of all components relevant to any form of planning that includes consideration of the *mission*, *enemy*, *terrain*, *troops* and *time* (METT-T). Table 1 lists the set of visualization skills that have been identified by SDS for training and their relationship to the components of METT-T.

Table 1 The set of trainable visualization skills and the component(s) of METT-T to which they are correlated.

	Skill	Related METT-T Component
1.	Visualizing 2D to 3D Terrain Correlation	Mission, Terrain
2.	Visualizing Optimal Cost for Terrain Traversal	Mission, Terrain
3.	Visualizing Line of Sight	Terrain
4.	Visualizing Distance	Enemy, Time
5.	Visualizing Dispersion	Enemy
6.	Visualizing Threat from Enemy Signature	Enemy
7.	Visualizing Trajectory	Enemy, Time
8.	Visualizing and Prioritizing Threat	Enemy
9.	Visualizing Formations	Enemy, Time
10.	Visualizing over Time	Time

Guidelines for Training

The processes used for training are as equally important to the effectiveness of training imparted to subjects as the technologies constituting the methods. Well designed processes can facilitate understanding and retention that are cornerstones of any training. For this reason, Tuskegee University has identified a broad set of guidelines for the processes to be employed in training the aforementioned visualization skills. They are as follows.

a. Train individual elements of the task separately. As proficiency and automaticity develop, integrate training sessions of individual elements with other elements (Schneider, 1985). In the context of NEXWARS and training for situation awareness, one could teach recognition of one element of METT-T factors through presenting various scenarios that teach recognition of one factor, such as the threat level. These may then be combined with another element, such as recognition of different types of terrain cover. The training device should be flexible enough to allow the incorporation of different elements mixed with other elements at the learner's discretion. This strategy also allows the learner to practice time-sharing skills, when attempting to recognize different METT-T patterns.

b. Ensure the learner engages in active participation throughout training. Requiring the learner to respond every few seconds helps to ensure that the learner remains active, thus improving the efficacy of practice time (Schneider, 1985).

c. Design many trials to practice critical skills.

d. Practice and Overlearning. Training on specific tasks should continue beyond one errorless trial. To ensure automaticity of the behavior/skill, learners should be required to practice a skill well beyond one errorless trial. This also significantly reduces errors. In addition, the learner should be allowed to control the number of trials he or she practices. By individualizing instruction, the learners monitor their own knowledge, and are more likely to engage in elaborative rehearsal (a technique to increase understanding and retention of information; Wickens & Hollands, 2000).

Individual Differences in Operators and Learners

There are a multitude of factors that may influence visualization skills and training strategies. First and foremost are individual differences between participants. For instance, in the realm of human-computer interaction, Crosby, Iding and Chin (2002) note that, "differences in people usually account for more variability in performance than differences in system design or training procedures." They cite Egan and Gomez's (1985) study that found age and spatial memory of subjects to influence performance in computer interaction 20 times greater than the variation due to the design of an editor. Therefore, an important element of any training package is to be able to assess the trainee's current proficiency level.

In recognition of the need to determine the proficiency of a user, SDS can incorporate a skill evaluation engine that determines the accuracy of the responses of a user to the questions posed during a training session. Based on the percentage of accurate responses, the engine can

draw some basic conclusions about the likely skill level of the user and generate the training scenario in a given iteration of the process based on the results from the previous iteration. Thus, the lower the score in a given iteration the lower the level of difficulty in the scenario generated in the next iteration. At the end of the sections describing the results of the research into developing visualization skills we shall describe the actual training methodology and the use of the engine.

Guidelines for Information Display

Determining an optimal information display methodology is a constant challenge.

a. If graphics are added to text, related information needs to be presented close together to foster integration of the material. (This reduces problems of divided attention; Wickens & Hollands, 2000.)

b. Presenting information using dual modalities reduces memory constraint. For instance, present verbal information as spoken, and visual information in the form of diagrams or graphics. Information is most likely to be attended to if it's in center of field of view.

c. When using color on displays, presenting consistent mapping between prior knowledge and current knowledge facilitates learning and reduces errors. Thus, for example, red indicates enemy or warning, etc. Limiting color coding to two or three levels of discrimination minimizes working memory constraints.

d. In case of terrain visualization, viewing angle and perspective will influence training for situation awareness. For example line-of-sight tracks can be better visualized using a 2D view as compared to a perspective view.

In the following sections we provide a detailed investigation on the technological foundations for training the various visualization skills we have identified earlier and the research tools necessary to facilitate the training of those skills. They form the core results derived by SDS from their research and development efforts during Phase I of this STTR. The feasibility of several technologies has been already demonstrated through the use of computer-generated animations and the feedback obtained from The Contracting Officer's Technical Representative (COTR) and other parties have been used to refine them further.

Results

SDS conducted an extensive amount of research during Phase I of this STTR to identify and develop technologies that could be harnessed to create feasible methods for training the visualization skills identified in various battlefield scenarios. This research identified many feasible technologies that could be developed atop the existing infrastructure of SDS' visual tools to train the visualization skills identified earlier. The implementation of these technologies is realizable within the time, scope and cost of a proposed Phase II for this project. Furthermore, within the scope of this research, SDS in conjunction with Tuskegee University, developed the basic outline of the processes to support the training of those visualization skills that were

economically and technically feasible. Each process is expected to yield measurable results in any given iteration of the process or learning trial such that those results can be used to drive the flow of control and the level of difficulty in future iterations. The following two sections describe the technical and training developments during Phase I and provide an overview of the training methods.

Technical Developments

This section provides a detailed description of the technical developments during Phase I for each of the visualization skills previously identified.

Visualizing 2D to 3D Terrain Correlation

To this day, a significant amount of visual information about the battlefield is conveyed through 2D contour maps. They serve as an indispensable tool for representing geographical features by succinctly describing their position, orientation and size (Banks & Wickens, 1999). However, they suffer from some serious handicaps. The interpretation and visualization of elevation and relief from the isolines of such maps is not a trivial task, because they offer little visual content beyond the outline of the cross sections of a terrain taken at uniformly spaced elevation planes. Visual supplements such as color and shading that can help in judging relief and terrain quality (i.e., its degree of smoothness or ruggedness) are often absent. Furthermore, a contour map is isomorphic to a top-down orthographic view, and is therefore devoid of perspective. Figure 1 illustrates this situation using a contour map of the 29 Palms Marine Corps Air Ground Combat Center (MCAGCC) on the left, and its corresponding top down view from an altitude of 23,000 meters on the right. The map is centered approximately over Hidalgo Mountain with the label *Marine Corps* decaled over it on the contour map. Note that, the top down view offers few visual cues regarding the relative elevations of the various natural features within it. For example, it is difficult to tell the relative height of the natural features that appear to be a range of mountains running from the southern end of the map to the northwestern corner.

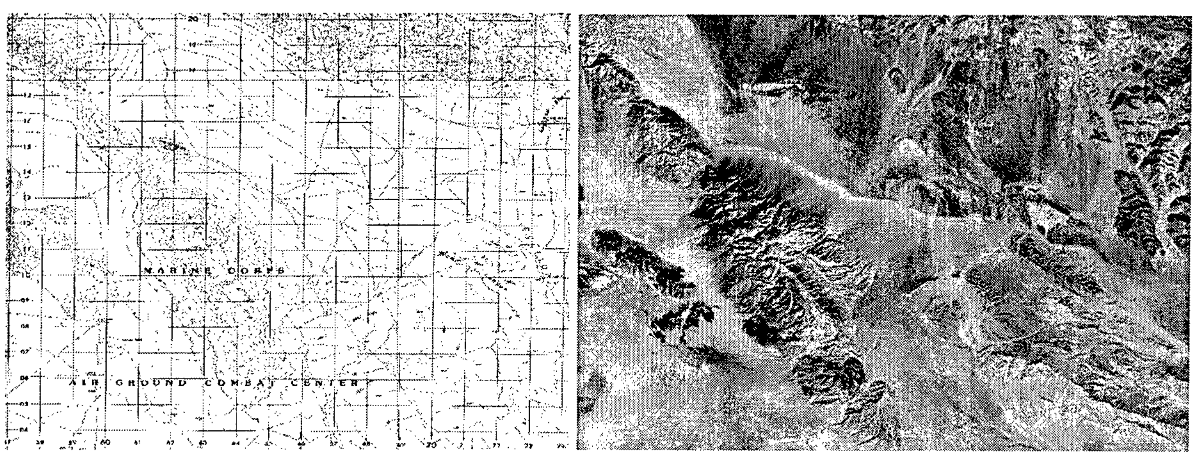

Figure 1. Contour map of 29 Palms, left, and its corresponding 3D view, right, rendered by SDS' IG.

On the other hand, near ground isometric views are naturally better suited to the cognitive abilities of humans, since cognitive mapping of streets, buildings, trees, terrain and landmarks are generally performed from ground-based positions and perspectives in 3D. Furthermore, they are visually rich with details that readily afford answers to questions such as the relative elevation of topographical features, line of sight between points and terrain composition (St. John, et al., 2001). However, near ground 3D perspective views have drawbacks too. They hide details that are positioned behind features in the line of sight and often render assessments of the size of features in the distance difficult. For example, Figure 2 displays a set of perspective views of the 29 Palms MCAGCC corresponding to the contour map in Figure 1. Each is obtained at a specific elevation in meters and a pitch value in degrees to capture approximately the same area displayed by the contour map in Figure 1. From top left, in clockwise order, the corresponding elevation and pitch values are: {10,000 m, -40^{0}}, {3000 m, -24^{0}}, {2000 m, -19^{0}} and {1000 m, -13^{0}} the elevation and pitch both decrease from an almost top down orthographic view to a near ground perspective view. Note that, the visual content facilitating the assessment of relative height, terrain quality, and line of sight is sequentially enhanced, while features at a distance are not only foreshortened but also get obscured by topography nearer to the observer. Each is obtained at an elevation in meters and a pitch value in degrees to capture

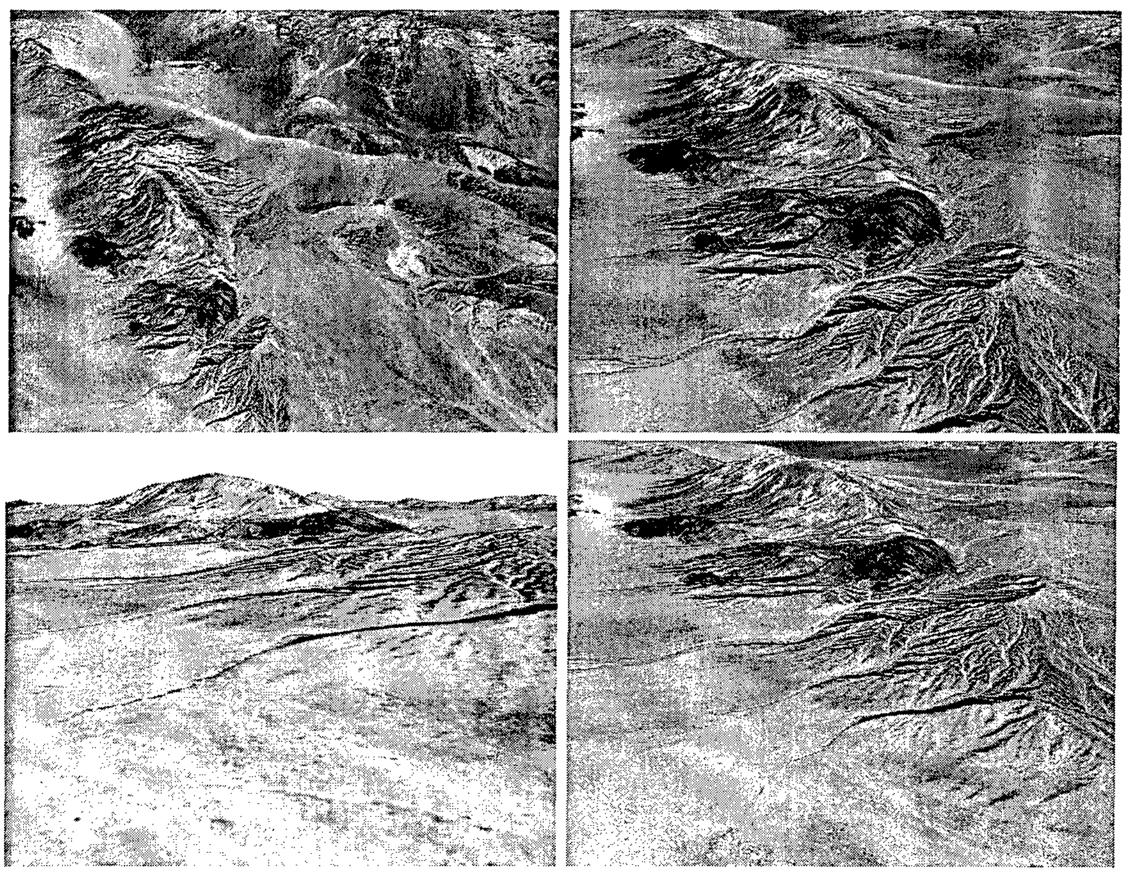

Figure 2. Set of perspective views of the 29 Palms generated by the SDS IG corresponding to the contour map in Figure 1.

approximately the same area displayed by the preceding contour map.

The need to see geographical features on a battlefield, in true scale, is critical to overall situational awareness (St. John, et al., 2001). For this reason, contour maps are indispensable. However, the need for visual information to be consistent with the natural cognitive interface of humans makes 3D perspective views equally important. Therefore, the ideal scenario is where one has both a contour map and an *eye-in-the-sky* to obtain a 3D perspective of the environment. Therefore, in the absence of one of the two, it is vital that the warfighter has the skills to extrapolate information from one to visualize the other. In the following paragraphs, we describe several issues in the visualization problem domain and the capabilities to be embodied by SDS' visualization tools to achieve the task of training the warfighter to develop their skills to address those issues.

As noted earlier, the ability to mentally translate 2D contour information into its corresponding 3D imagery, and vice-versa, is an important skill that enables warfighters to achieve a high level of awareness about their environment. In recognition of this fact, simulation and training systems should ideally embody a comprehensive set of functionalities to enable them to train and enhance this skill. Using these functionalities, subjects can translate 2D contours into visual forms that are morphologically an intermediate step in the visualization sequence from 2D to 3D. To accurately characterize the intermediate morphologies, we first describe the prospective visual correlations between 2D and 3D imagery.

Ridge/Valley Detection and Highlighting. Consider, the two maps given in Figure 3. The top down 3D view of the mountain on the right appears to match the topographical feature centered in the contour map for at least two reasons. The first is evident from the shapes of the tightly spaced partial or complete convex hulls (Foley, et al., 1995) on the contour map that define the faces of the mountain. The isolines in Figure 3 between 800 and 900 meters define a set of partial convex hulls, while the isolines above 900 meters up to 1000 meters define a set of complete convex hulls. It is fairly easy to see that these convex hulls closely match the shape of the corresponding faces on the top down view.

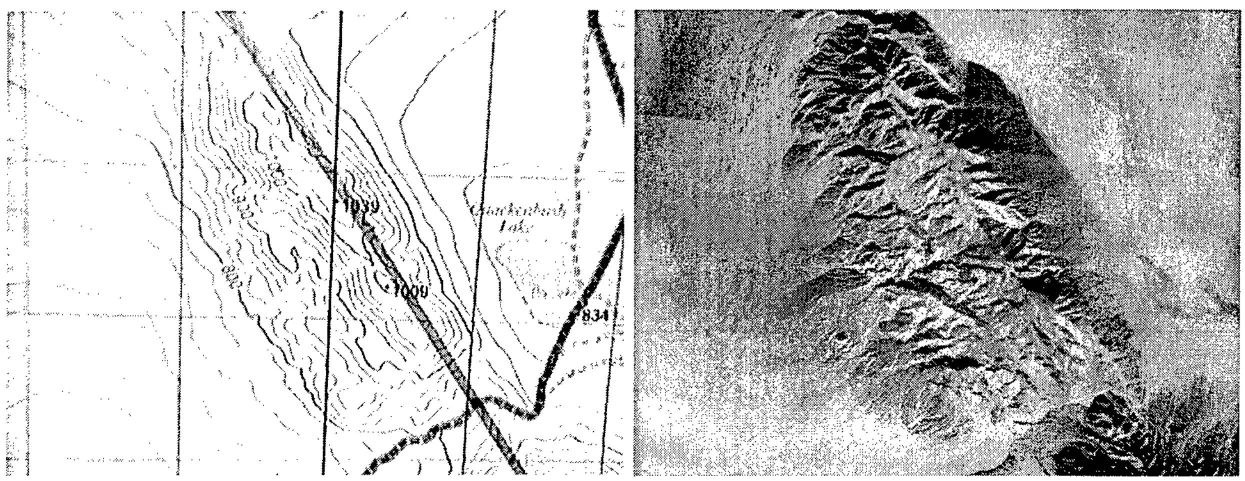

Figure 3. Section of the Hidalgo mountain range at 29 Palms.

The second reason is obtained by considering points on each isoline that are the midpoints of arcs with a high arc to chord ratio (Philips & Rosenfeld, 1987). The spline (Gallier, 1999) derived by joining such a set of proximal points defines the line where two distinct faces with different aspects intersect to forming a ridge or a trough. A set of such splines can be used to uniquely characterize each topographical feature that is investigated. Figure 4 displays a set of points on isolines highlighted by circles that are the midpoints of arcs with a high arc to chord ratio.

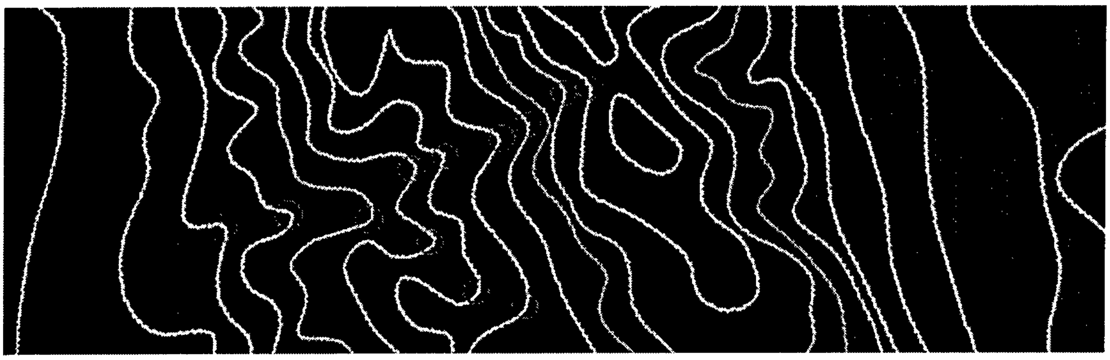

Figure 4. Set of isolines displaying arcs highlighted by circles that have a high arc to chord ratio.

Similarly, Figure 5 displays a set of dots over the points on the isolines on the southwestern face of the mountain that are the midpoints of arcs having a high arc to chord ratio. In this case, each dot corresponds to a point on a trough, and the graph obtained by connecting together the points that are closest to each other forms a trident shaped pattern. We note that the corresponding points on the 3D top down view shown on the right exhibits a similar pattern due to the effect of natural lighting in which the troughs appear in darker shade. The presence of such patterns on natural terrain therefore can be used to identify topographical features uniquely.

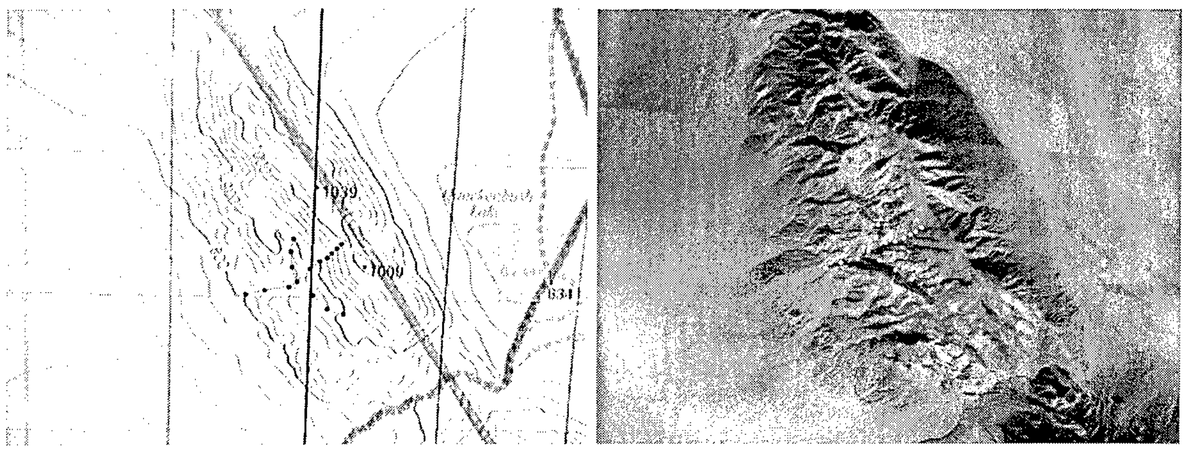

Figure 5. A section of Hidalgo mountain range on 29 Palms shown in a contour map on the left displaying a proximal set of points on isolines.

The usefulness of such pattern matching is evident when viewing topographical features at perspectives at a pitch close to 0. For instance the image on the right in Figure 6 displays the same section of the Hidalgo mountain range on the 29 Palms MCAGCC shown in the contour map to its left. However, they visually appear unrelated even to subjects in the Marine Corps familiar with that range. But, upon consideration of the pattern formed by the aforementioned splines, we can see that the contour map on the left and the 3D perspective image on the right have a common topographical signature. Such signatures can help subjects decide whether the two images represent the same topographical feature. In fact, spatial navigation research has shown that the memorization of such distinctive features is an important factor in cognitive mapping and its preservation over extended periods of time (Sadalla, et al., 1980).

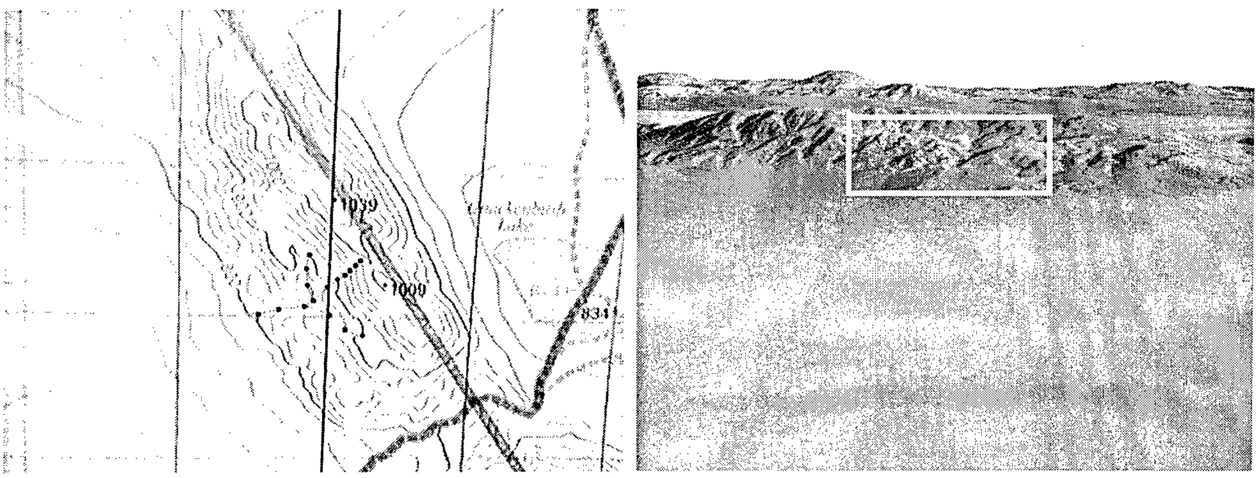

Figure 6. A section of 29 Palms on the left displaying a proximal set of points on isolines that are the midpoints of arcs with a high arc to chord ratio. The crowfoot shaped pattern is clearly visible within the blue rectangle overlaid on the corresponding 3D perspective view on the right generated by the SDS IG.

We assume that the isolines are generated using splines on a set of vertices defining a convex hull. With this assumption we can determine all the midpoints of arcs with a high arc to chord ratio on all splines as follows. We take a set of M vertices $\{u_1, u_2, \ldots, u_M\}$, where M is odd, and determine if the ratio of the sum of the distances between u_1 to u_2, u_2 to u_3, …, u_{N-1} to u_N, and u_1 to u_N exceeds a predefined threshold R. If it does, then the midpoint $u_{(N+1)/2}$ is the desired point on a crevasse or a ridge.

One of the issues that has to be dealt with following the determination of midpoints of arcs with a high arc to chord ratio is how to filter out those points that are not members of a significantly large or prominent feature. The method applied to eliminate smaller or insignificant features which refers to the midpoints of arcs with a high arc to chord ratio as vertices. First, create a graph comprised of components (i.e., connected sub-graphs), where two vertices in a component are adjacent if they have a distance less than a predefined threshold. Next, delete all components with order (i.e., the number of vertices) less than a predefined threshold. Finally, color each edge with a suitable color to visually demarcate it from its background.

Figure 7 describes the pseudo code for the algorithm for detecting and highlighting ridges and valleys on isolines. Let $S = \{s_0, s_1, \ldots, s_{N-1}\}$ be the set of all splines each defining an isoline in a contour map, and ordered by elevation. Let R be the threshold which an arc to chord ratio must exceed to be a point of a crevasse or ridge. Assume that two vertices less than D distance apart are considered to be adjacent in a component. Finally, let Z be the minimum desired size of each component in the derived graph.

for $i \leftarrow 0$ *to* $(N-1)$ *do*
{
    $T[i] \leftarrow 0$;   // The number of midpoints on spline s_i
    Let $s_i = \{v_{i_1}, v_{i_2}, \ldots, v_{i_N}\}$ be the set of points defining each spline;
    for $k \leftarrow i_1$ *to* i_N *do*
    {
        if $\left(\sum_{j=k}^{(k+M) \bmod M} d(v_k, v_{k+1}) / d(v_k, v_{(k+M) \bmod M}) > R \right)$ *then*
        { $P[i, T[i]] \leftarrow v_{(k+M)/2}$; $T[i] \leftarrow T[i] + 1$;   }
    }
}

// At this point the array P contains $T[i]$ midpoints corresponding to each spline s_i.
// Next we connected suitable adjacent vertices between successive splines in the ordered set.

for $i \leftarrow 0$ *to* $(N-2)$ *do*
{
    for $j \leftarrow 0$ to $(T[i]-1)$ *do*
    {
        for $k \leftarrow 0$ to $(T[i+1]-1)$ *do*
        {
            if $(d(P[i,j], P[i+1,k]) < D)$ *then*
                attach $P[i+1,k]$ to a unidirectional link from $P[i,j]$;
        }
    }
}

// At this point we have graph with multiple connected components.
// We have to get rid of those components that are insignificant. i.e., of size less than Z.

// Recurse depth-first from each vertex in $P[]$, and count the number of descendants on)
// the search tree. If the sum upon completion of the search is less than Z, then delete each
// vertex in that tree.

(continued on next page)

```
for i ← 0 to (N − 1) do
{
    count = DepthFirstCount(P[i, k]);
    if (count < Z)
    {
        DepthFirstDelete(P[i, k]);
    }
}
// At the end of this procedure, we have the required result which is a graph
comprised of    // components that are each of order greater than or equal to Z.
// The methods DepthFirstCount and DepthFirstDelete are defined as follows.

integer DepthFirstCount(v)
{
    integer count = 0;
    for each vertex w linked to v do
    {
        count = count + DepthFirstCount(w);
    }
    return count;
}

void DepthFirstDelete(v)
{
    for each vertex w linked to v do
    {
        DepthFirstDelete(w);
    }
    delete vertex v;
}

// End of algorithm for deriving and highlighting crevasses and ridges visible on
contours.
```

Figure 7. Pseudo code to derive the ridges and crevasses on topography from isolines.

DTED Transformation into an Elevation Graph. Image generators typically represent 3D imagery by draping suitable textures over polygons whose vertices are defined by *Digital Terrain Elevation Data* (DTED). The DTED is generally given as a uniform grid with a specific inter-post (i.e., inter-vertex) distance of 100 (Level 1), 30 (Level 2) or 5 (Level 3) meters. We can then apply the following set of steps to transform a given DTED set into an elevation graph that resembles a contour map.

a. Partition the vertices of the DTED using a step function into elevation strata. For instance, if each partition is centered at an altitude that is a multiple of *M* meters, then we can classify the vertex *v* into its corresponding partition using the partitioning function, $h(v) = (height(v) + M/2)\ mod\ M$. Upon application of the function *h*, we note that vertices in the same strata (i.e., partition) are assigned the same elevation.

b. Create components (i.e., a connected set of vertices) on the DTED's vertex set by joining any neighboring vertices that belong to the same stratum with an edge. Note that, each vertex in a DTED has 8 neighbors at the north, south, east, west, northeast, northwest, southeast and southwest corners. This ensures that the vertices that define each isoline lie in a unique component. Each component can be created using a recursive search method as illustrated in Figure 8.

```
// We assume that all the vertices in the DTED's vertex set V are stored in some data
// structure using which the state of vertices can be obtained. Thus, the method
// GetVertexNotInAComponent uses this data structure to find the next available
vertex that is // not claimed by a component. An actual component number is some positive
valued integer // that will be assigned to every vertex. Let the function component(v) denote
the component // number of v.
        n ← 1;
        v ← GetVertexNotInAComponent();
        while (v exists) do
        {
            CreateComponent(v, n);
            n++;
            v ← GetVertexNotInAComponent();
        }
// Start with any vertex v that has not been claimed by any component up to this time
and n is // the component number to be assigned to all vertices that qualify into this
component
        void CreateComponent(v, n)
        {
            for each vertex w that is a neighbor of v do
            {
                if ((component(w) = 0) && h(w) = h(v)) then // h is the step function
defined in (a)
                {
                        CreateComponent(w, n););
                        create the edge (v, w);
                        component(v) ← n;
                }
            }
        }
// End of algorithm for creating components.
```

Figure 8. Method to create components of vertices within the same stratum.

c. Derive the convex hull for each component and delete all internal vertices. There are a number of well-known techniques for deriving convex hulls such as the "package wrapping" and "Graham scan" methods (Sedgewick, 1992).

d. Replacing the edges connecting all the existing vertices in a component with colored splines such that, splines at lower elevations are colored using darker colors (or shades of gray) while those at higher elevations are colored using brighter ones. The method for creating splines is well documented (Foley et al., 1995) and fairly straightforward.

The application of steps (a) through (d) will render an image with the vertices in any stratum being non-adjacent to vertices in a different stratum. Furthermore, the vertices within a stratum will form a connected component that closely approximates contours. For instance, consider the rectangular contour section of the Hidalgo mountain range shown on the left in Figure 9. It has a dimension of approximately 4 km (width) by 3 km (height). Given a DTED with an inter-post spacing of 30 meters, the grid corresponding to that section would have approximately 133 (width) by 100 vertices (height). Figure 9 displays the isolines that may be generated using the DTED corresponding to the 3D image to its left. In this image, the outermost convex hulls are colored against a bluish-black background to permit subjects to easily discern and correlate the shapes of the 3D image and its corresponding elevation graph.

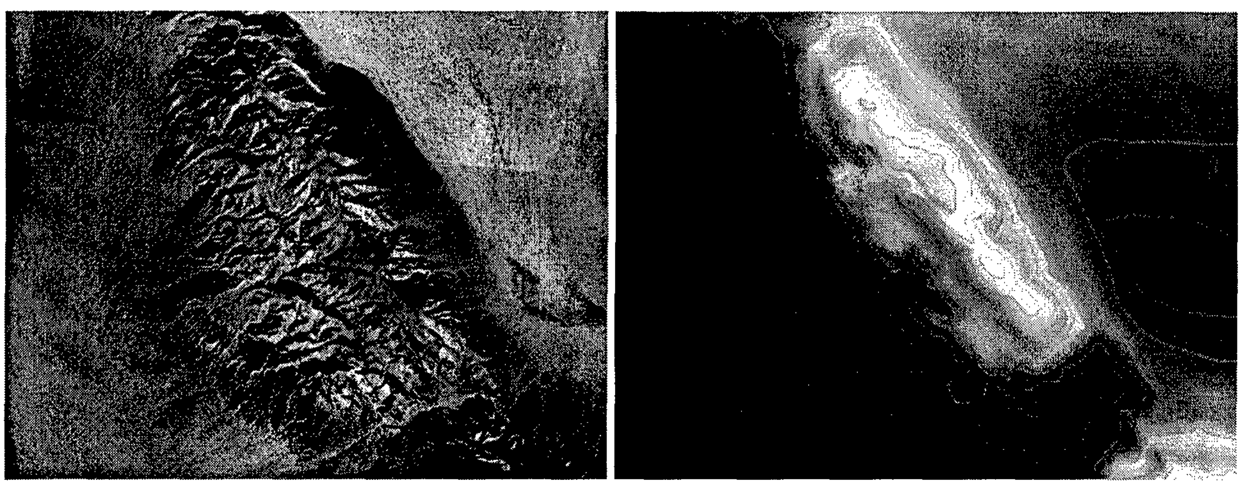

Figure 9. Top down view of the elevation graph prospectively generated by the SDS IG from DTED.

Note that, since the elevation graph contains vertices embedded with height information, an image generator can display them as a 3D image. This permits the splines of the elevation graph to be viewed from perspectives other than from top down, and visually correlated to their corresponding 3D and 2D counterparts. Therefore, they may be used as intermediate steps in the visualization sequence necessary to morph a 2D contour map into its 3D counterpart. Figure 10 displays the splines of the elevation graph generated from the DTED as seen from two separate perspectives.

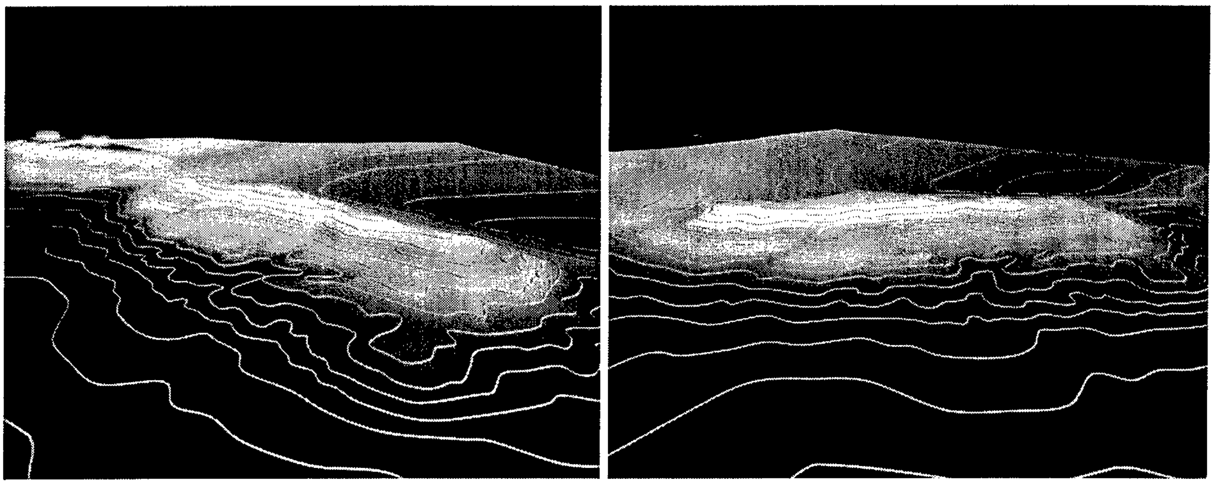

Figure 10. Elevation graphs displaying the section of the Hidalgo Mountain shown on the left of Figure 9 as viewed from two separate perspectives.

Image generators can easily embody the capability to translate any 3D imagery to its corresponding elevation graph, or an elevation graph to its equivalent contour map, and display each of these to the subject. The functionality to perform such visual morphing will permit subjects to obtain multiple views of a battlefield and accurately visualize their environment in response to a task (Barnes & Wickens, 1998). The elevation splines can then be colored with natural colors conforming to the terrain to aid their recognition and correspondence with their 3D counterparts (Wichmann & Sharpe, 2002). In fact, Figure 11 displays the effect of coloring the elevated splines with colors akin the natural coloring of the topography. Note that, the use of natural colors with lighting serves to clearly define the crowfoot shaped pattern highlighted earlier in Figure 6 in the images on the right side of both Figure 10 and 11.

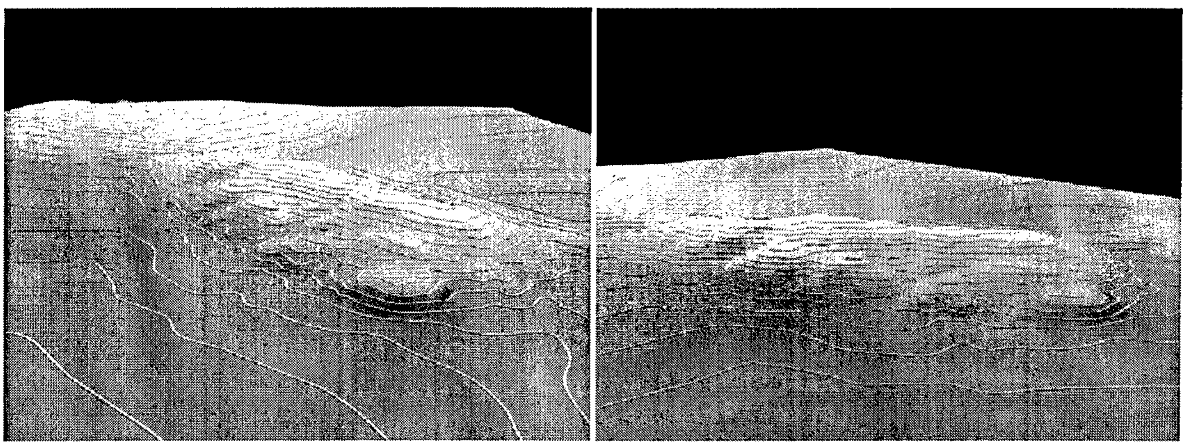

Figure 11. Elevation graphs displaying the section of the Hidalgo Mountain shown on the left of Figure 9 as viewed from two separate perspectives using natural colors.

The SDS' NEXWARS will provide subjects the ability to dynamically instruct the SDS IG to display imagery in any of three forms – as a 3D perspective, an elevation graph, or a contour map. A slider bar on NEXWARS will permit the subject to smoothly transition from flat

2D contours on one extremity to 3D perspectives on the other, with elevation graphs in the center.

Visualizing Line-of-Sight

A challenge to the warfighter is the visualization of the existence of line of sight (LOS) to points of tactical interest on a battlefield. For example, if subjects are given locations on a terrain where an enemy force is positioned, can they identify areas on the terrain where they can obtain concealment for their own forces without inhibiting their maneuverability or defensive punch? Similar problems relating to LOS include the identification of points on the terrain from where the area that can be placed under surveillance or covering fire is maximized. Such tasks are not easy when subjects iteratively consider the line of sight between every pair of positions over an expansive terrain with rich topographical detail. The AAcuity® PC-IG can provide an intuitively appealing method for subjects to visualize the solution to this problem in the following manner.

Given a terrain and a finite set of points on that terrain to which LOS is to be determined, the AAcuity® PC-IG will ascribe to each point in that set an omni-directional point of light and derive the corresponding 3D shading on the terrain. Note that, all sources of ambient light such as the sun or moon shall be discarded for this purpose. Then, the areas that are not shadowed have LOS to the set of points, and vice-versa. This is similar to the manner in which commercial systems such as the Manifold® 3D View Studio™ displays visibility between zones and points on a given terrain.

SDS' NEXWARS can permit the user to insert the points on the terrain to which LOS is to be determined as distinct objects using a combination of a joystick and/or mouse. The objects design should ensure that their function is intuitive from their form and also minimizes their invasiveness in the overall scene.

Figure 12 displays a section of the Hidalgo mountain range from a pitch of –30 degrees with the LOS to be determined to four points on the terrain from the area surrounding it. Those four points are each ascribed an omni-directional point of light. The lights are used to shade the surrounding area in the absence of all other ambient sources. It is then very easy to see that the shadowed areas on the mountain range offer concealment from those four points, and conversely, areas that are lighted have LOS to at least one of those four points on the terrain. Note that, the points of light shown in Figure 12 are in close proximity to each other, with approximately 200 meters separating the points that are the farthest apart. The distances between such points in alternative scenarios on the SDS image generator are not intended to be, nor shall be, restricted to any specific value.

Figure 12. Section of the Hidalgo mountain range shaded with respect to four points of omni-directional light.

In the preceding description for visualizing LOS to a set of points, the position of those points do not vary with time. The AAcuity® PC-IG can extend the design to enable subjects to visualize the existence of LOS to a set of dynamic points on the terrain. For example, if an enemy force is advancing along a given trajectory, the areas on the terrain that afford concealment from that force over a span of time would be under shadow during that time. This provides valuable insight into the areas on the terrain where defensive forces may be positioned to prolong the duration of their cover and maximize the element of surprise prior to initiating engagement (USA FM 3-97.6). Figure 13 displays, from top left in clockwise order, a sequence of snapshots of four entities moving in a single file, with each entity affixed with an omni-directional source of light. The illumination of the surrounding areas changes as they gain or lose LOS to the set of dynamic entities over time.

The use of omni-directional lights to derive LOS as shown in Figure 13, is for the purpose of illustration only. In reality, entities such as tanks and armored personnel carriers afford rather limited field of views. Therefore, to accurately visualize the LOS with respect to such entities, the SDS image generator can construct statistical models to simulate their sweep and field of view and illuminate the surrounding topography accordingly.

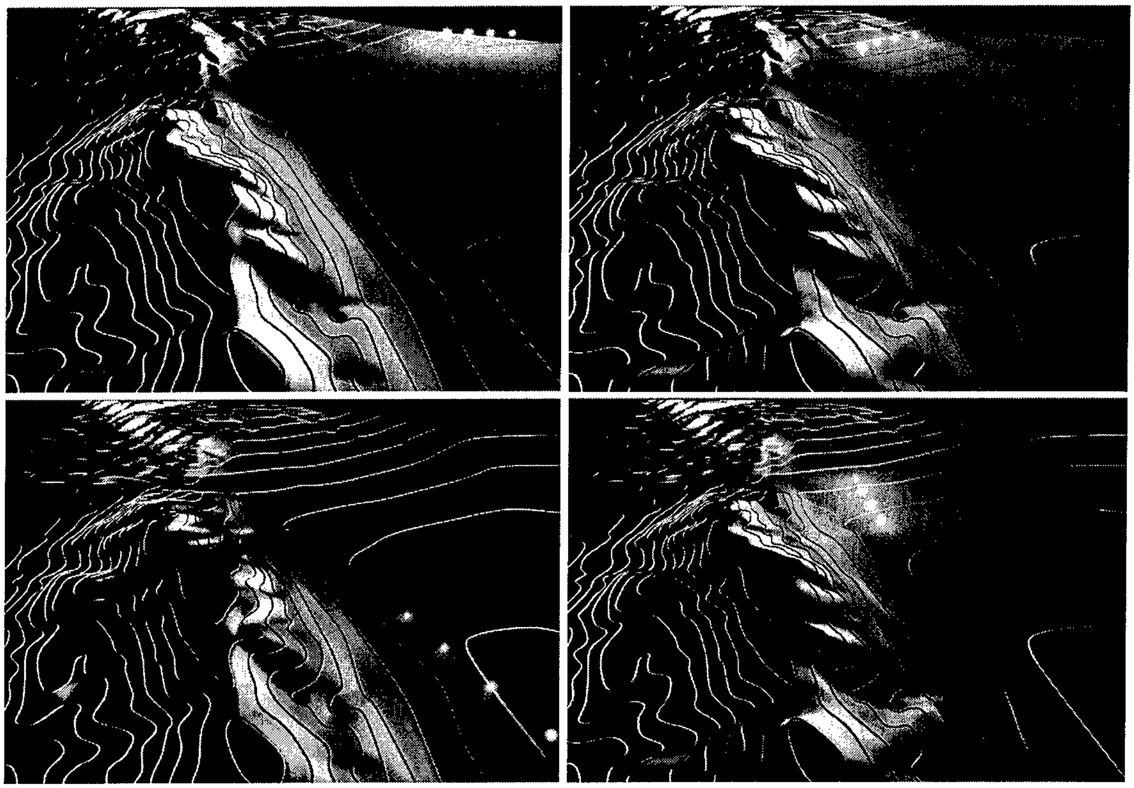

Figure 13. Sequence of frames, top clockwise, displaying four entities, moving single file each with omni-directional light.

Figure 14 displays, from top left in clockwise order, a sequence of snapshots of four entities moving in a single file, with each entity assigned a directional source of light to approximate a field of view of 45 degrees. Each snapshot captures the orientation of the entities' viewpoints at that instant which changes periodically to sweep the surrounding terrain for potential enemy.

The illumination to display the existence of LOS in Figure 13 and 14 are achieved using ideal weather conditions and lighting that does not experience any attenuation. The reality is, factors such as rain and fog and distance significantly affect visibility. Hence, the AAcuity® PC-IG shall accommodate common environmental criteria and distance into its lighting model to achieve illumination and thereby, the corresponding visualization of LOS that is more consistent with the real world.

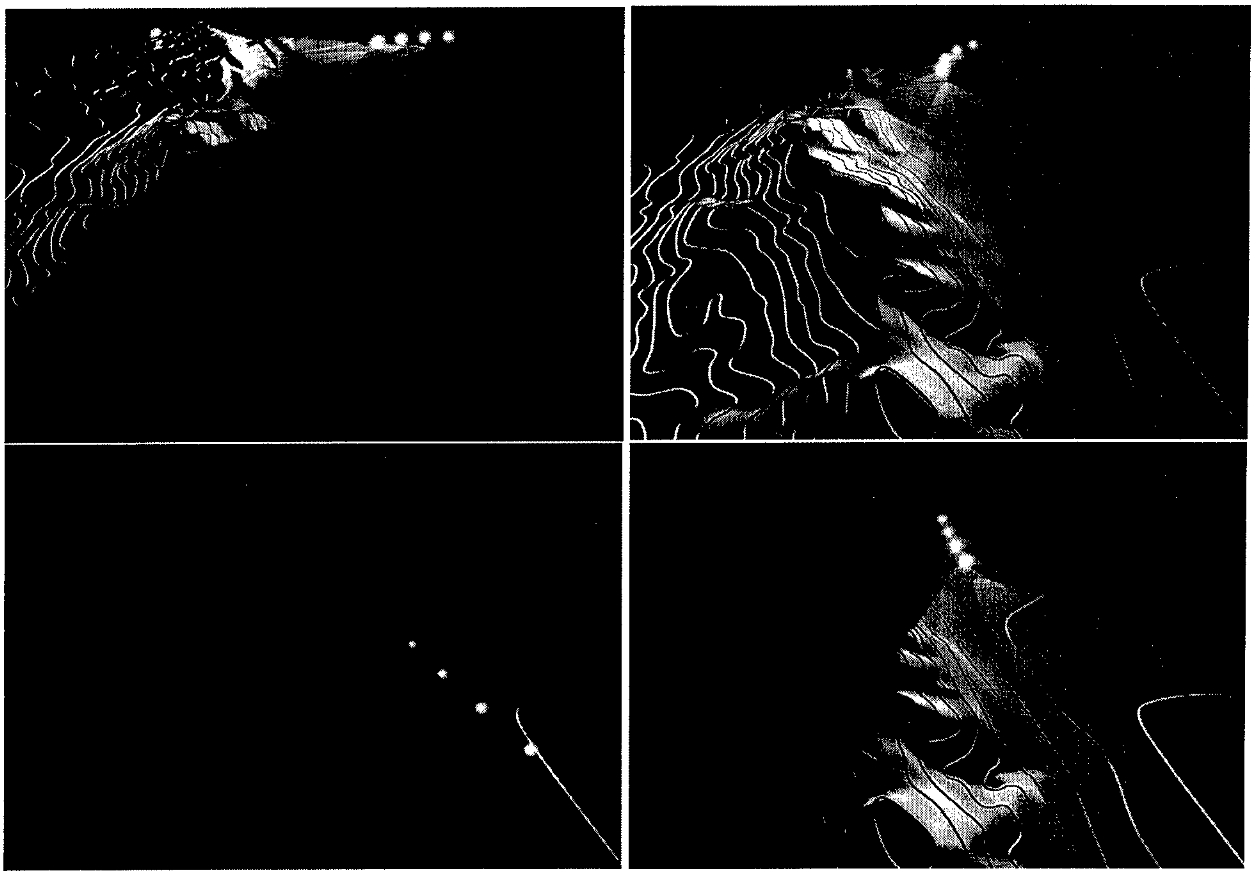

Figure 14. Sequence of frames clockwise display four entities moving in a single file.

Visualizing Optimal Cost for Traversing Terrain

The ability to judge the cost of traversing a given terrain – where cost is a function of time and the risks to survival – and visualize the most economical route from a large set of candidate paths is a cognitive skill that is invaluable to the warfighter. It is important to military planners both defensively and offensively since "soil trafficability, especially when considered in conjunction with climatic conditions, is a very important factor in evaluating cross-country movement", US Army Field Manual on Countermobility, (USA FM 5-102). This fact has been historically highlighted by the experiences of the Anglo Canadian forces during the Dieppe landing in World War II, which ended in a disaster due to the failure of their mission planners to judge the impassable nature of the obstacles on the beach at Dieppe and its loose pebble surface that neutralized their tanks (Ford & Gerrard, 2003).

The cost of a route may be obtained from the weighted sum of the values of independent variables affecting the subject's ability to use that route. The set of variables may include criteria such as, the distance between the two endpoints of the path, contour of the terrain traversed by the path derived from DTED, the type of vehicle (if any) being used by the subject and the presence of obstacles in the prospective path. An extensive list of the various obstacles is given in the USA FM 5-102. A user may then plot a course from one position to another using a pointer akin to the *green hand* currently deployed by SDS' NEXWARS and obtain the cost of the described path.

The tool proposed by SDS is different from standard trafficability analysis engines such as the one proposed by Slocum, et al., (2002) and offers automation in deriving the most economical path joining two arbitrary points on a terrain. In contemporary trafficability analysis engines, the user chooses a candidate path to be used for navigating from one point to another, and describes that path to the engine, whereupon, the engine computes the cost of that path and displays it to the user. The cost is of course determined from a variety of criteria that is accommodated by the engine. When the value of a certain criterion associated with a segment of a path is unknown in such an engine, the cost is displayed as a value with a given mean and a corresponding standard deviation. The mean and standard deviation in turn are derived from the set of costs obtained by plugging in expected values for those criteria that are undefined for various segments in a path. The shortcoming of these engines is that, they are limited to offering information on only those paths that are specified by the user. In other words, they are oblivious to the presence of paths that are more economical than those defined by the user. This can be a significant handicap when the distance between the source and destination is too far to visually identify all prospective paths between them and/or the contour of the spanning terrain is complex. In such situations the user may be unable to visually identify all prospective paths for submission to the engine for cost analysis. This in turn results in the user having less than optimal solutions.

In contrast, the tool proposed by SDS shall automatically derive and display the most economical path along with its cost, or a set of the most economical paths ordered by their cost. This accuracy of the derivation is independent of the distance between the source and the destination or the form of topography between them. The advantage of such a scheme is that the subject is no longer burdened with visualizing and specifying all candidate paths for cost analysis.

For example, Figure 15 illustrates the two most economical routes derived and plotted by the SDS engine from a source indicated by the yellow flag (front right) to the destination marked by the (left) green flag for a tank. The cost associated with each route is represented by a numerical value displayed in close proximity to that route and is normalized with respect to the most expensive known route. The more expensive of the two routes is indicated by the dotted blue colored path traversing over terrain that is shorter than but not as flat as the green colored path (right) from the source to the destination. The derivation of such routes weighs in factors such as, the type of entity for which the route being constructed, AAcuity® PC-IG generates the numerical cost of each and normalizes both by the more expensive route, which in this case is the dotted blue colored one. The displayed cost will therefore always be a real value in the range of 0 – 1.0.

AAcuity® PC-IG can estimate the most economical route from one point to another by the application of Dijkstra's algorithm (Figure 16) on a weighted digraph derived from a DTED (Mitchell & Papadimitriou, 1991). The SDS image generator can then display the most economical path computed between two points over a section of terrain and display it to the subject to train their cognitive abilities to estimate the relative cost of traversing that terrain. The digraph is comprised of a uniformly spaced grid of vertices between the source and the destination, with each vertex corresponding to a post on a DTED, and each edge assigned the

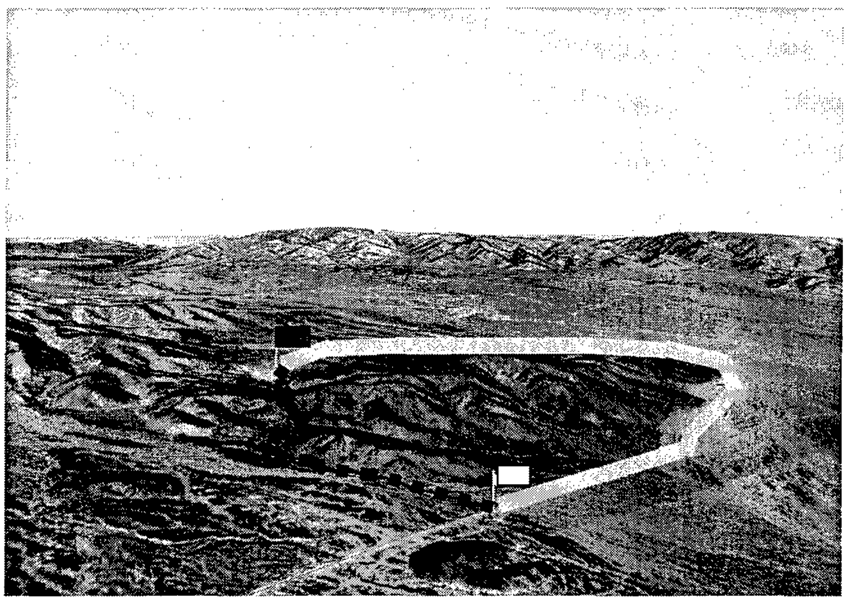

Figure 15. Section of the terrain displaying two candidate routes from a source indicated by the yellow flag to the destination marked by the green flag for a tank.

cost of traversing between the corresponding pair of vertices. For instance, if the destination is 3 km from the source on a terrain obtained from a level-2 DTED with an inter-post spacing of 30 meters, the corresponding digraph would have at least 10,000 vertices and over 49,902 cost-labeled edges. This is observed from the recurrence relation: $e(n + 1) = e(n) + 10n - 6$ for a graph laid out in a square grid with each vertex adjacent to vertices to east, west, north, south, north-east, north-west, south-east and south-west directions, where $e(n)$ is the number of edges in a $n \times n$ grid. This recurrence relation admits the solution $e(n) = n(5n - 1) + 2$.

```
Array [2 ... N] Dijkstra(L [1... N, 1 ... N])
{
    C ← {2, 3, ... N}; S ← N – C;
    For i ← 2 to N do
        D [i] ← L [1, i];

    repeat (N – 2) times
    {
        v ← element of C that minimizes D [v];
        C ← C – {v}; S ← S + {v};
        for each w in C do
            D [w] ← Minimum {D [w], D [v] + L [v, w]};
    }
    return D;
}
```

Figure 16. Dijkstra's algorithm applied to a graph comprised of weighted edges on $N \times N$ vertices.

We observe that such a graph is not symmetrical. That is, the cost of traversing from point A to point B may not be the same as the cost of traversing from point B to point A. This asymmetry may result from numerous factors. For instance, if point A is at a higher altitude than point B, we would expect the cost of traveling from A to B to be cheaper than from B to A. Similarly, if a river has to be forded to travel between points C and D, with C upstream to D, then it would be cheaper to travel from C to D than from D to C. This is a computationally intensive problem that can be solved efficiently and quickly by AAcuity® PC-IG. Naturally, the lesser the inter-post distance in the DTED, the greater the accuracy of the estimated cost for each prospective path, and the determination of the least expensive path. Dijkstra's algorithm may be expressed by the following pseudo-code that computes the least cost from the vertex $D[1]$ to $(N-1)$ reachable vertices $D[2]$ through $D[N]$.

An alternative method for calculating cost is Floyd's algorithm (Figure 17), where the cost between all pairs of vertices in a graph is evaluated. This is an expensive method having computational cost of $O(N^3)$ that is suitable for preprocessing larger graphs. In comparison, Dijkstra's algorithm has computational cost of $O(N^2)$. However, once a graph has been preprocessed, the time taken to obtain the cost between a pair of vertices is limited to only that for swapping the relevant data into system memory from secondary storage. The only caveat to employing such a preprocessing technique is the inversely proportional relationship between file size and the corresponding speed with which it can be swapped into memory. Hence, vertex pair cost information may have to be distributed over multiple files such that each file is small enough to be loaded into memory easily; yet large enough to contain pairs of vertices at sufficient distances to have practical value. For example, if on average users need to find least expensive paths at intervals of every 5 km, then the number of pairs of vertices with cost values in each file with 30 meter post intervals must exceed 27889 (167 x 167). Floyd's algorithm may be expressed by the following pseudo-code that computes the least cost between every pair of N vertices and returns it in the array $D[1 \ldots N, 1 \ldots N]$.

```
Array [1 … N, 1 … N] Floyd (L [1… N, 1 … N])
{
    Array D [1 … N, 1 … N];
    D ← L;

    for k ← 1 to N do
        for i ← 1 to N do
            for j ← 1 to N do
                D [i, j] ← Minimum {D [i, j], D [i, k] + D [k, j]};

    return D;
}
```

Figure 17. Floyd's algorithm applied to a graph comprised of weighted edges on N x N vertices.

The SDS IG shall compute the most economical path between two points over a section of terrain, decal and display it to the subject to train their cognitive abilities to interpret the

relative cost of traversing that terrain. Figure 18 illustrates the wire frame generated by the SDS IG over which suitable textures are draped to render realistic geo-specific 3D topography. In fact this wire frame constitutes the underlying structure of the topography that is displayed in Figure 15. The vertex at the confluence of two or more wires corresponds to a DTED post derived from satellite. At each such vertex, the value of each criterion in the set of criteria that includes elevation and soil composition is evaluated. The edges between two vertices are then assigned a composite weight derived from the weighted mean of the values of the aforementioned criteria at the end vertices and the distance between them. This set of vertices and the edges on them forms the graph on which we can apply the previously discussed algorithms.

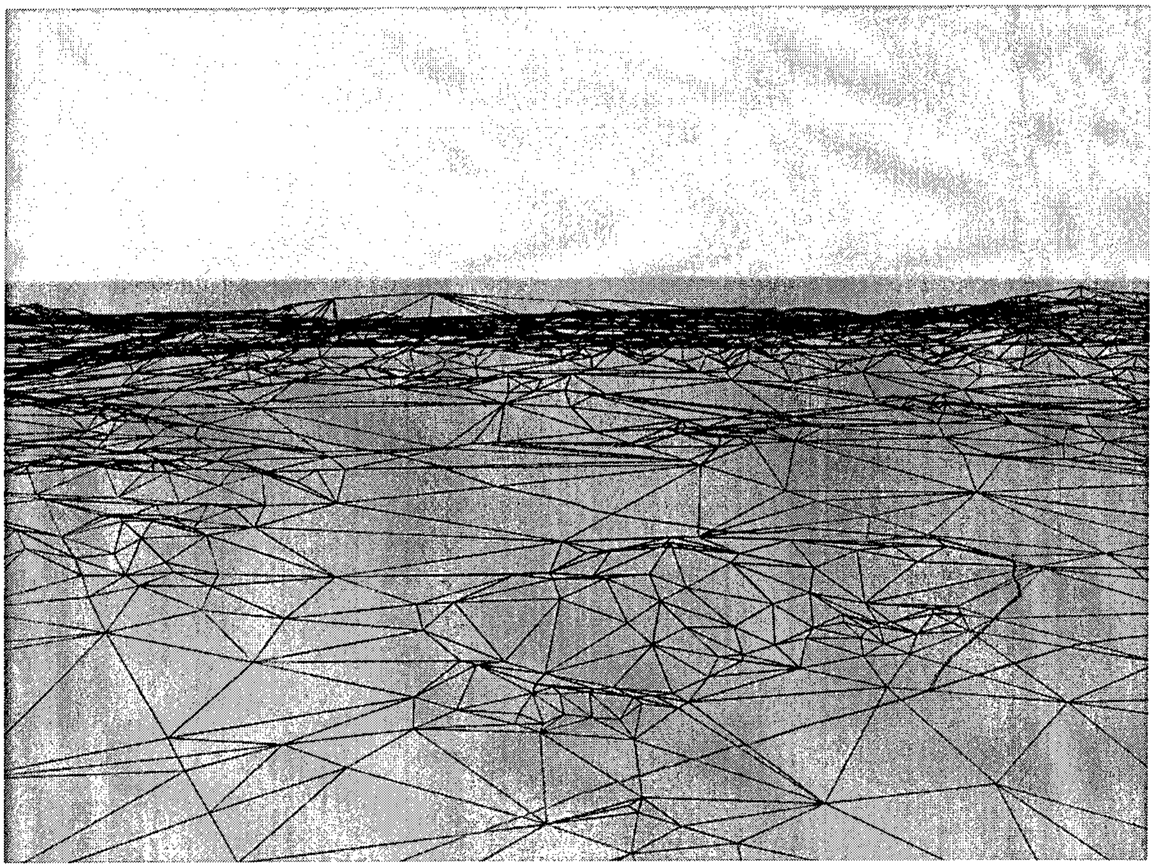

Figure 18. Wire frame of a section of terrain on the 29 Palms MCAGCC.

Visualizing Distance

The ability to judge the distance is an invaluable asset required by many warfighters in a variety of tactical situations (USA FM 23-10, FM 71-3, FM 17-12-8). It is a challenging task on featureless terrains or on unfamiliar ones that offer few natural frames of reference. There are a number of ways in which warfighters are instructed to obtain the distance to an entity (USA FM 6-30). In no particular order, they are as follows.

i. Use of laser range finders. They offer unparalleled accuracy – to almost within a meter – and are the preferred tool of the warfighter in the battlefield. Furthermore, they can

enhance a subject's ability to ascertain distances to entities using suitable frames of reference by iteratively refining the accuracy of their estimations through validation and/or correction. In acknowledgment of this fact, Spectator/NEXWARS will provide subjects a simulated laser range finder with which they can target visible entities using a joystick or mouse, and obtain their distances. Figure 19 displays an image from the SDS IG with an M1A1 tank that has been lased by the observer to obtain its distance. The distance is shown above the laser sights to be 513.69 meters. It is also acknowledged that warfighters may not have access to laser range finders in the battlefield, and therefore, NEXWARS needs to provide functionalities to train the necessary cognitive skills of subjects for estimating distance. These are described next.

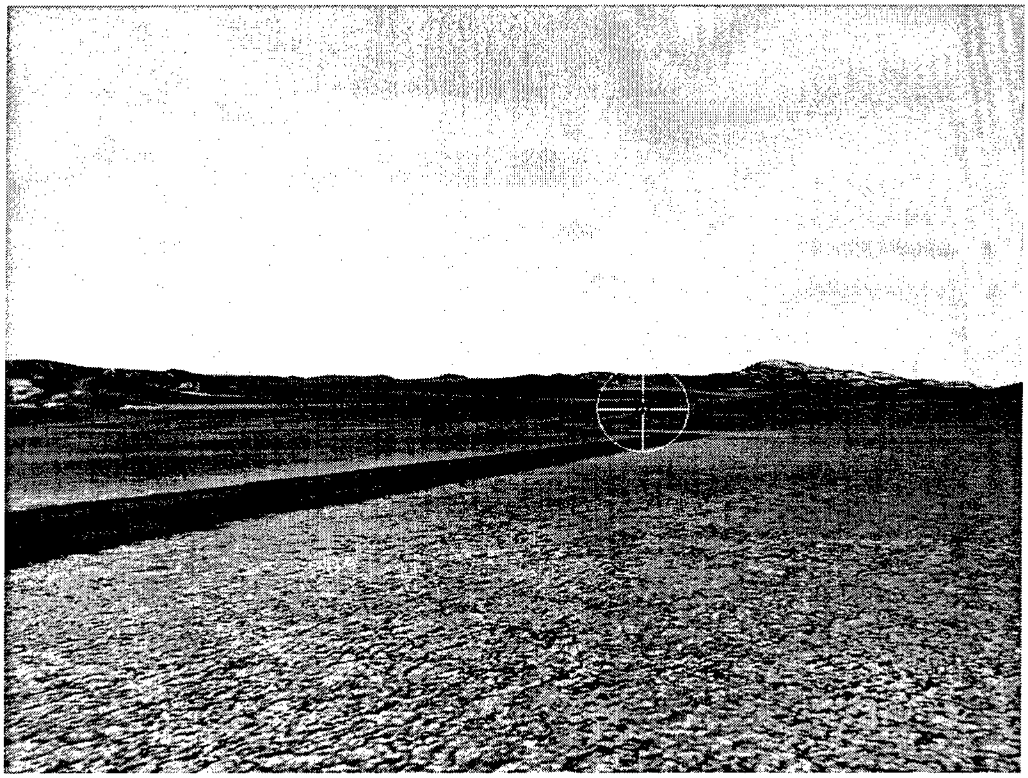

Figure 19. Image from SDS' IG displaying an M1A1 tank on a road in the 29 Palms MCAGCC.

ii. Flash-to-bang method. This is a useful technique by which the observer can estimate the distance to an entity by noting the difference in time between the observed muzzle flash of that entity or one near it and the corresponding sound reaching the observer. Sound travels at a speed of 340.29 meters per second at sea level, which is approximately 1 km every 3 seconds. Therefore, if the difference in time between the observed muzzle flash and its corresponding sound reaching the observer is t seconds, then the entity is at a distance of $t/3$ kilometers. The SDS IG can integrate a suitable sound effects package to play realistic sounds when rendering components of its particle system such as explosions and muzzle flashes. The particle system effect sound will be played with volume and delay commensurate to the distance of the observer from the point at which the effect is being rendered to simulate the time lag between the visual and auditory components of the effect reaching the observer. This will permit subjects to train their skill in estimating distances to various targets.

iii. The visualization of posts to the target at every 100 (or 200) meters for a distance of up to 500 (or 1000) meters. Naturally, from an observer's perspective, the visible length of the intervals between the visualized posts will be more compressed as the angle of incidence between the line of sight and the line formed by the sequence of posts decreases. However, for most practical purposes, at a height of approximately 6' above the terrain the posts appear reasonably separated when running along the terrain to the target starting on the terrain directly below the viewpoint.

The SDS IG will overlay posts in 3D space at equidistant intervals defined by the subject to training their capability to visualize them for the purpose of estimating distances. Figure 20 illustrates a sequence of yellow colored posts running along the terrain parallel to the line of sight between the subject and the target. In the figure, the target is an M1A1 tank at a distance of approximately 500 meters from the observer on a road in the 29 Palms MCAGCC. The observer's viewpoint is approximately 6' above the terrain. Note that, with progressing distance the separation between the visualized posts decrease. Hence for estimating entities at greater distances it is important for the subject to visualize posts at greater intervals, say 200 meters as opposed to 100. The SDS NEXWARS will provide suitable functionality for the subject to chose the intervals between the posts displayed by the SDS IG to enable them to practice distance estimation for entities placed at varying ranges from the observer – near, medium and long.

The SDS IG will also allow subjects to alter the offset between the line formed by the posts and the line of sight of the observer to the target. The subject can obtain a greater separation between the posts by increasing the corresponding value of the offset. Of course, the subject has to be mindful of the limitations of human memory. Therefore only a finite number of images of a sequence of posts corresponding to a given offset should be committed to memory for subsequent recall during visualization.

Since methods (ii) and (iii) rely specifically on the natural cognitive skills of the subject, their accuracy in each iteration of an exercise may be verified by the use of (i).

A corollary to determining the distance to a specified entity is determining its speed, given that speed is the rate of change of distance over an interval of time. Since speed is typically used to estimate an entity's time of arrival at a given destination or boundary, such derivations may be a qualitative assessment which an observer could use to determine an entity's time of arrival.

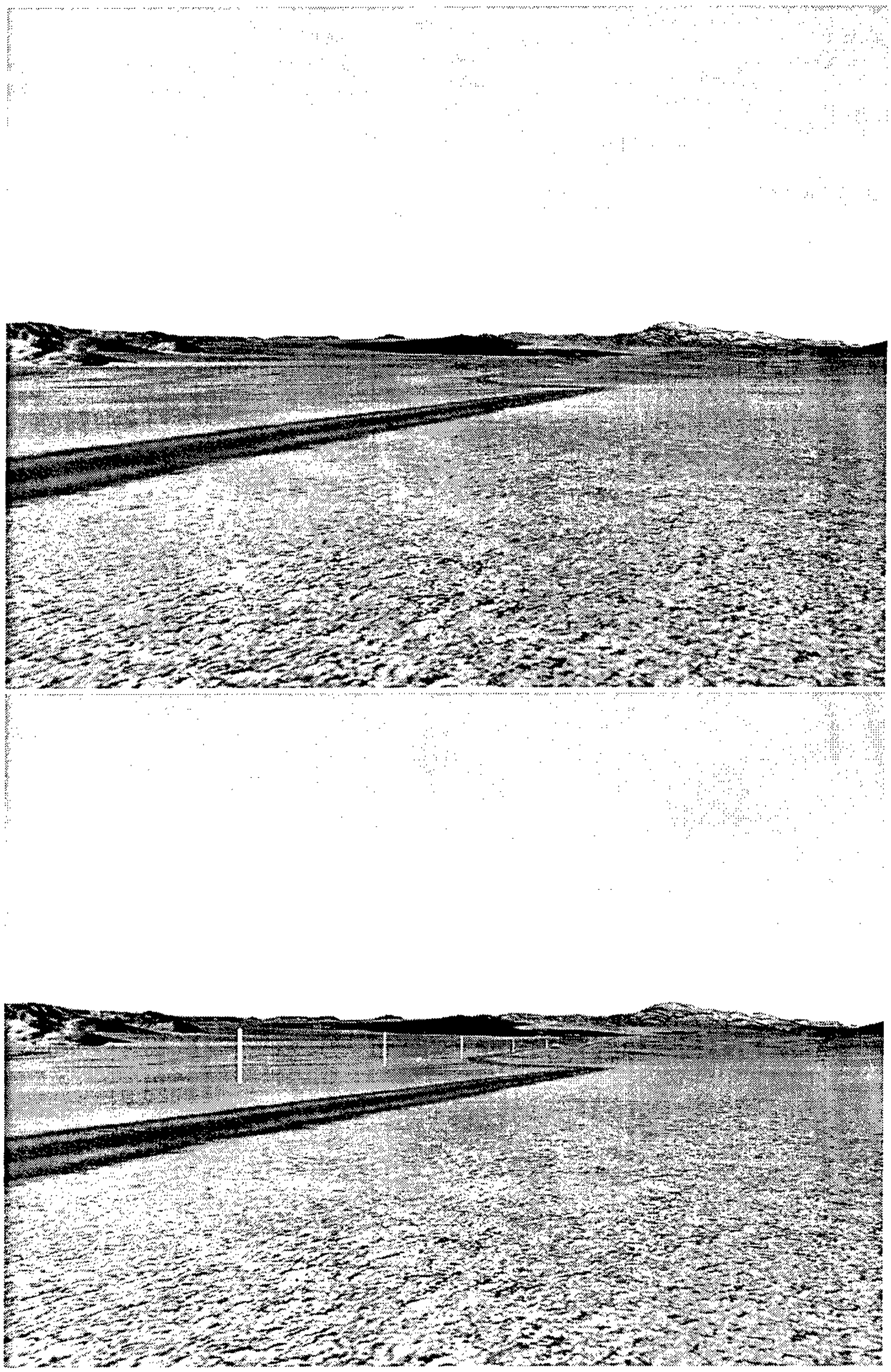

Figure 20. Images from the SDS IG showing an M1A1 tank 500 meters from the observer. The overlaid yellow colored posts run parallel to the line of sight of the observer to the tank to aid visualization of distance over the terrain. The top image shows the posts in a line offset 2 meters below, while the bottom one shows the posts in a line offset 30 meters to the left of the observer's line of sight to the tank.

Visualizing Dispersion

The use of dispersion, i.e., separation between entities, as an instrument to achieve subterfuge and enhance survivability on the battlefield is common (USA FM 7-10). Hence, the ability to estimate the dispersion of an enemy formation is an important skill to the warfighter. For example, an accurate assessment of the dispersion of an enemy formation is valuable to supporting air assets to enable them to neutralize that formation. As another example, the dispersion of a formation in conjunction with its trajectory provides the observer valuable hints about its potential focus and targets.

NEXWARS will provide subjects a visual overlay of the graduations of a protractor in degrees to enable them to see the angular separation between any pair of entities in a formation. Subjects may then obtain the distance to any one of the entities by either estimation (using one of the previously described methods) or through the use of the simulated laser range finder. Using this distance, the angular separation between the two entities and a few basic trigonometric values committed to memory, a subject can estimate the distance between the entities. Table 2 provides some values for the distance between two entities δ as a function of the distance to one entity d and their angular separation θ in degrees. It assumes that the two entities are approximately equidistant. The values displayed for δ are approximations to the value of $2d \cdot tan^{-1}(\theta/2)$.

Table 2. Distance between a pair of entities as a function of the distance to one, and their angular separation

Angular Separation θ (Degrees)	**Distance Between Entities δ**
6	$d/10$
12	$d/5$
20	$d/3$
30	$d/2$

It is easy to observe from Table 2 that, the value of δ divided θ is a constant equaling $d/60$. Thus, the subject can derive the dispersion between a pair of entities δ for most angular separation values of θ other than those given in Table 2 by employing the formula:

$$\delta = d\theta/60, \text{ for } \theta \leq 30^{\circ}. \qquad (E1)$$

The reason for the linear behavior of this function is due to the fact that the graph of the inverse tangent function is fairly linear for small values of its argument.

Figure 21 displays an image from the SDS IG with two tanks approximately equidistant from the observer at $d = 500$ meters. The angular separation θ between the tanks is seen from the overlaid protractor to be 15 degrees. Hence from equation $E1$, we have the dispersion between the tanks as $\delta = 500 \cdot 15/60$, that equals 125 meters.

Note that the estimation of dispersion relies upon the successful visualization of two independent factors – distance to at least one of the entities and the angular separation between them. The NEXWARS can permit subjects to then verify their estimates by clamping the Stealth to one of the two entities in the pair and observing the distance to the other entity from the Stealth. The distances from the Stealth to each visible entity is currently displayed by NEXWARS in text boxes above the respective entities.

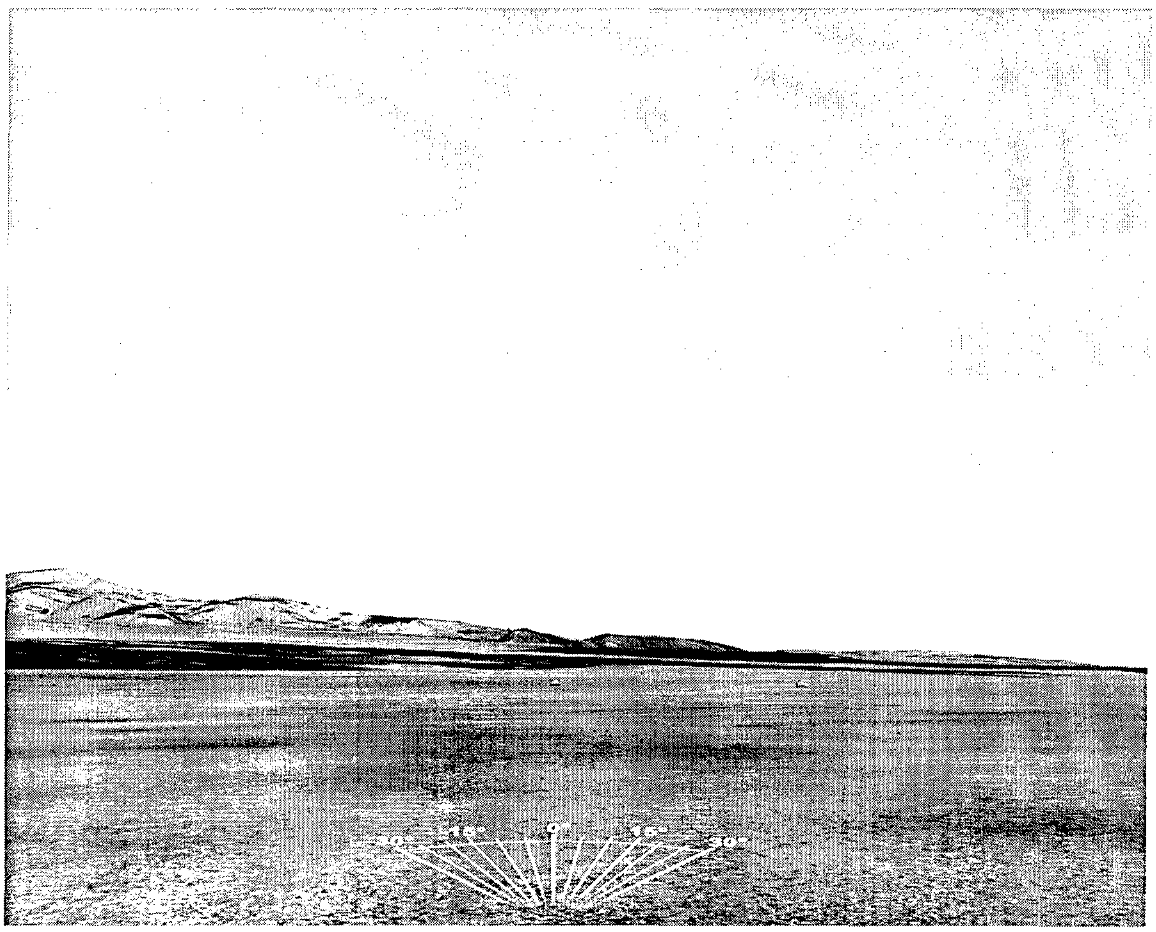

Figure 21. Two M1A1 tanks displayed at a distance of approximately 500 meters each from the observer with an angular separation of 15 degrees shown on the overlaid protractor.

Visualizing Trajectory and Position in the Future

Visualizing the trajectory of ground-based entities is a challenging task for a number of reasons. Unlike aircraft, they move at considerably slower speeds and can change heading within a fixed distance numerous times. Consequently, the length of the path traversed by ground-based entities within a small window of time is generally neither sufficient in length nor constant in its orientation. This poses difficulty to the observer when extrapolating their trajectories and therefore their positions in the future.

The SDS IG will provide subjects with the trajectory visualization functionalities similar to the LucentVision's virtual replay (Pingali, et al., 1999 and 2001). LucentVision currently features in sports such as tennis and soccer. It uses real-time video analysis to obtain the trajectories of players and the ball, and offers a rich set of visualization options based on this trajectory data. Using this scheme, a subject can observe the path traversed by an entity from a specific time in the past up to that moment as a sequence of snapshots of the entity at its corresponding position at intervening points in time, superimposed upon the live image. This path history then facilitates the ability of the subject to gauge the trajectory of the entity and estimate its likely position at points in time in the future.

To achieve the aforementioned functionality the SDS IG will maintain the history for each entity's location, orientation and action in an exercise over a finite distance over the terrain. Thus, a subject's request to see the path taken by an entity up to that time can be fulfilled by superimposing snapshots of that entity from uniformly spaced points in time in the past upon the live image. To prevent the attention of the subject swaying away from the live entity, the snapshots will be presented with increased fading i.e., greater transparency applied to those that are from farther back in time. Note that, the trajectory estimation tool is ideally applied to a small set of entities to prevent cluttering.

Figure 22 shows an image rendered by the SDS IG with the path taken by a T-72 tank illustrated using a sequence of snapshots of its positions at four points in time in the past, in addition to its current position taken at equidistant intervals. The sequence conspicuously highlights the trajectory of the tank and affords the viewer a more tangible basis on which to estimate its position in the future. The transparency of the snapshots is greater for those farther back in time – 20% for the first one preceding the live image up to 80% for that which is farthest back in time, in steps of 20%. The transparency values can be adjusted to offer better distinction with respect to the live image using feedback from user trials. Note that, while the image displayed in Figure 22 illustrates the captured history of the T-72 over a span of approximately 200 meters, the applicability of this feature is not limited to that distance. The subject using NEXWARS can dynamically adjust the distance over which the history of an entity is to be displayed and the number of snapshots to be displayed in the intervening distance. Furthermore, the pitch of the camera can be adjusted to any desired value to capture the scenario at perspectives that offer the subject the most informative view.

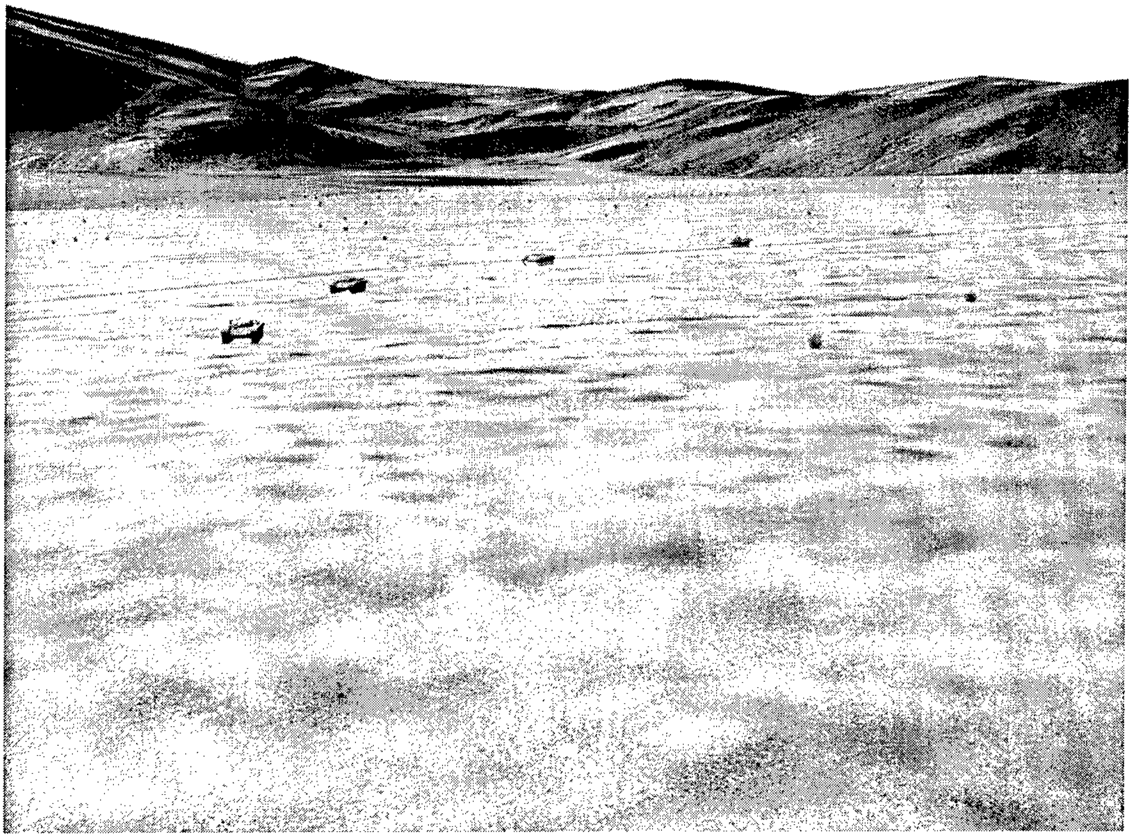

Figure 22. Image rendered by the SDS IG showing the path taken by a T-72 tank using a sequence of snapshots of its positions at four points in time in the past, in addition to its current position.

The SDS IG can also supplement the display of an entity's history with its projected path using a Bayesian model (DeGroot & Schervish, 2001). In such a model we assume that the change of orientation of an entity is correlated to at least the following random variables.

i. Rate of change of orientation
ii. Change of velocity, i.e., acceleration (or deceleration).

We illustrate the manner in which the model works using the following example. Let us consider the random variables given in (i) and (ii). We would like to determine the probability of a change of orientation by θ degrees at an instant in time given that we have seen a rate of change of orientation of φ degrees per second in the immediately preceding instance of time. We derive this using the observed values for the following events in any instance of time – the probability of the change of orientation of entity e being θ degrees, the probability that the rate of change of orientation of entity e being φ degrees per second, and the probability that the rate of change of orientation of entity e is φ degrees per second when the change of orientation of entity e is θ degrees in the instance following it.

We then define the following events necessary for constructing the Bayesian estimation for the probability of the occurrence of a specific change in orientation.

Event A Change of orientation of entity e is θ degrees in iteration i.
Event B Rate of change of orientation of entity e is φ degrees per second in iteration $(i-1)$.
$p(A)$ This is the probability that the change of orientation of entity e is θ degrees in iteration i.
$p(B)$ This is the probability that the rate of change of orientation of entity e is φ degrees per second in iteration $(i-1)$.
$p(B|A)$ This is the probability that the rate of change of orientation of entity e is φ degrees per second in iteration $(i-1)$ when the change of orientation of entity e is θ degrees in iteration i. Note that, this value is easily derived from past observations.
$p(A|B)$ This is the probability that the change of orientation of entity e is θ degrees in iteration i when the rate of change of orientation of entity e is φ degrees per second in iteration $(i-1)$.

From Bayes' Theorem we know that, $p(A|B) = p(B|A)p(A)/p(B)$.

Thus, we can derive the probability that the change of orientation of entity e is θ degrees in iteration i when the rate of change of orientation of entity e is φ degrees per second in iteration $(i-1)$. Thus, we can derive the value of $p(A|B)$ in a given iteration (other than the first) from the known values of $p(B|A)$, $p(A)$ and $p(B)$. We evaluate the values of $p(A)$, $p(B)$, $p(A|B)$ and $p(B|A)$ as follows. We divide the sample spaces for the likely values of an entity's orientation in degrees and its rate of change of orientation in degrees per second into intervals such that any value in an interval is assigned the mean value of that interval. In this manner we can isolate the values of an entity's orientation θ and its rate of change of orientation φ each to a finite set of values S_θ and $S\varphi$ respectively. Then, the value of $p(A)$ is the ratio of the number of instances where the entity's change of orientation is θ degrees, where θ is one of the finite values in S_θ. Similarly, the value of $p(B)$ is the ratio of the number of instances where the entity's rate of change of orientation is φ degrees per second, where φ is one of the finite values in S_φ. Finally, the value of $p(B|A)$ is the ratio of the number of instances where the entity's rate of change of orientation is φ degrees per second amongst those instances where the entity's change of orientation is θ degrees, where θ and φ are finite values in S_θ and S_φ respectively.

We note that we can substitute the random variable used for defining event B with suitable alternatives. For example, we may define the event B as the change of velocity of an entity. Then, we derive this using the observed values for the following events in any instance of time – the probability of the change of orientation of entity e being θ degrees, the probability that the acceleration of velocity of entity e being a meters per second square, and the probability that the acceleration of entity e is a meters per second square when the change of orientation of entity e is θ degrees in the instance following it. Now, for each value of θ, the Bayesian model will generate a corresponding probability. We may consider the position of the entity upon application of a given value of θ derived for a particular instance in time (i.e., iteration) with a relatively high probability as the starting point for generating the next value of θ for the next instance in time (i.e., the next iteration). We iterate in this manner until we have multiple sequences of values of θ indicating the likely changes of trajectory over time. One may visualize this as multiple threads, with each thread interspersed with points. At each point, the probability

of a change in trajectory is estimated and applied to get the next point on that thread. Thus, there is no unique sequence of values of θ corresponding to iterations from the present moment to future points in time that can be used to display the likely trajectory. Rather, it may be display within a pair of bound lines formed by the points on the aforementioned threads with cutoff probability values outside of which the trajectory is considered unlikely to exist. This cutoff value may be generated dynamically for an entity by deriving the probability with which it deviates outside of an estimated value of θ with a probability of p over multiple iterations. We may choose a value of p as the cutoff if, say, it accommodates two standard deviations of all changes in trajectories, i.e., only 5% of all changes in trajectories exceed any predicted value of θ with probability p.

The bounds may be displayed using modified forms of *Semi Transparent Meta Knowledge* (SMTK) objects that are an integral part of the SDS IG and are currently used to delineate areas over a terrain. The color scheme and the degree of transparency to be assigned to such SMTK objects will be firmly established following user evaluation so as to suit the visual interface of the average subject. Figure 23 displays the simulated history and the SMTK objects – bounding the likely trajectory of the tank in the foreground. Note that the

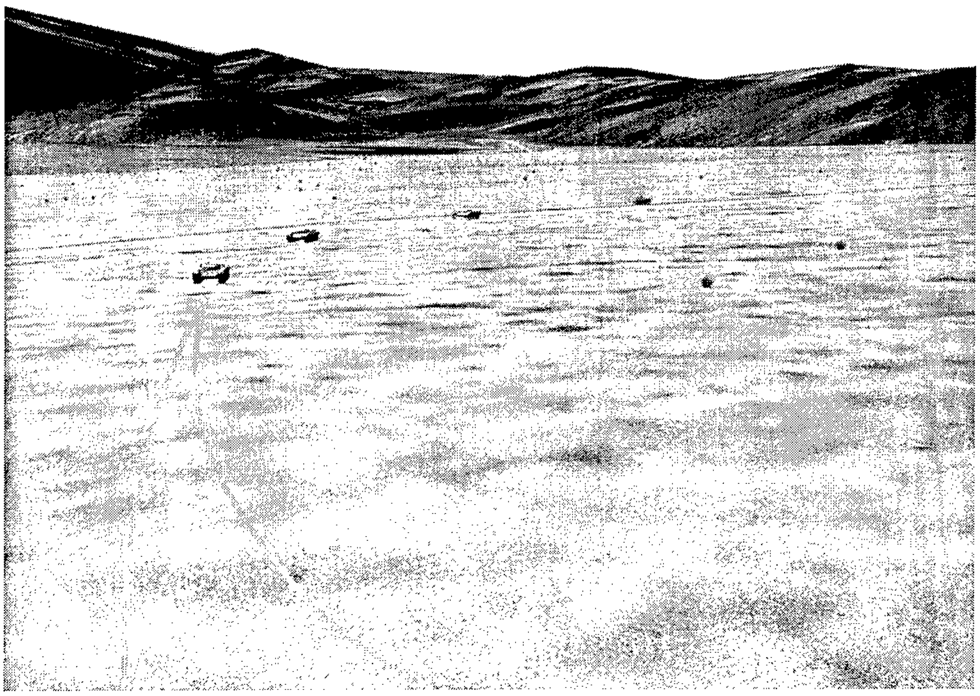

Figure 23. Illustration of the use of Bayesian models to predict the trajectory of an entity. The example uses the correlation between the change of orientation and the rate of change of orientation to predict the trajectory of the tank shown in the foreground. The turquoise colored lines are the bounds of the predicted trajectory simulating *SMTK* objects.

bounds simply indicate the limits within which the trajectory may lie. Note that, this example displays the projected trajectory over a short distance only to accommodate history and

projections within the same illustration. In practice, they may be represented separately and the trajectory of each entity projected over far greater distances.

Trajectories when combined with an analysis of the speed of an entity can yield interesting predictions on the position of that entity in the future. Naturally, it is logical to correlate the speed of a vehicle to the trafficability of the terrain being traversed.

Visualizing Threat From Entity Signature

The ability to detect targets from their signatures is invaluable to the warfighter. There are numerous signatures generated by each entity on the battlefield – be it a Soldier or a vehicle (USA FM 17-12-8), and their accurate identification and correlation to the generating source is vital to the warrior's success in offense and defense. Not only is the identification of signatures important, but so its interpretation to derive estimations for the size of the corresponding force and its orientation. For example, contemporary military thinking asserts that, "Daytime vehicular movement eliminates nearly any possibility of surprise, as dust trail created by the traffic can be spotted for miles" (USA FM 90-3). A corollary to this is, that it is equally important for the defense to ascertain the size and heading of the attacking formation to enable them to counter effectively.

Some of the questions that arise in this context are as follows. From a dust trail alone, can a subject estimate the number of entities in the formation and the heading of that formation? Can a subject estimate the number of entities in a formation from their tire and/or treads? We may assume that the trails are generated over soft terrain (desert or packed earth) and that the entities are not moving in a single file to cover their individual footprint. We may also assume that there are some natural points of reference on the terrain from which a subject is able to judge the size of the dust trail. For example, Figure 24 displays the dust trail that may be generated by entities hidden from the observer by a hill while traversing over loose soil. The observer can evaluate the size of the dust trail by first ascertaining the distance to it, and then estimating the number of entities that might generate a dust trail of that size on the terrain with a known soil composition.

The SDS AAcuity® PC-IG currently provides basic primitives for generating realistic dust trails for entities traveling over terrain with loose soil. Currently their size and form are independent of the entity generating them and environmental factors such as wind and rain. Hence, these basic primitives will have to be extended in future development to ensure that the size and form of dust trails are a function of the entities generating them, the direction and speed of the prevailing winds and the dampening effects experienced by the intensity of rainfall if any.

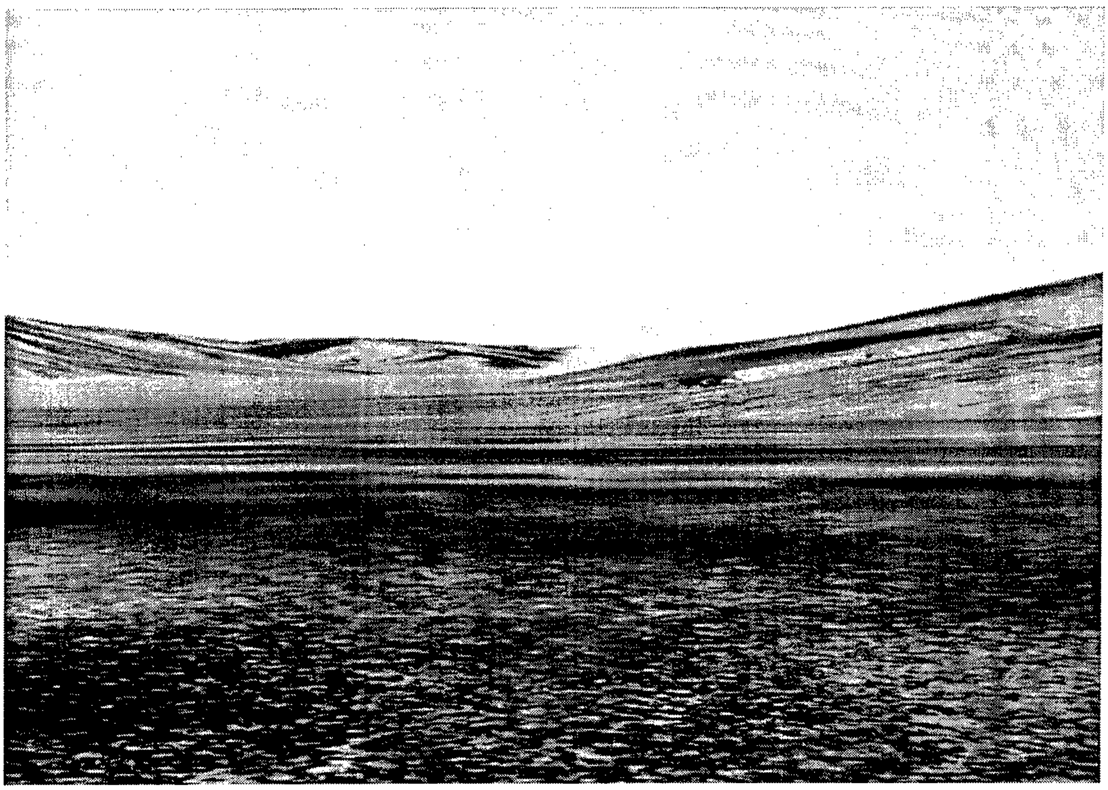

Figure 24. A display of the dust trail that can be generated by entities hidden from the observer by the hill in the foreground.

Visualizing and Prioritizing Threat

The ability to identify and prioritize threats is an important skill vital to the survival of the warfighter and its unit. The degree of threat posed to an observer by a recognized adversary may be judged using a combination of criteria such as the adversary's kill-range, the likely direction of its focus based on its aspect and orientation, and the level of exposure of the observer to that adversary. SDS' NEXWARS can quantitatively analyze the aforementioned criteria for an entity using Distributed Interactive Simulation/High Level Architecture (DIS/HLA) simulation data and instruct the AAcuity® PC-IG to display suitable visual cues to the observer to indicate the degree of danger posed by that entity.

The use of visual cues for indicating the status and disposition of an entity is not new to the AAcuity® PC-IG. The use of standard US military 2525B (MIL-STD-2525B) symbols to display an entity's type, position and distance from the observer has been a stated requirement of clients such as the US Marine Corps, which in turn has led to its incorporation into the AAcuity® PC-IG. In fact, the value of this feature in a variety of military applications has led to its assimilation into SDS' suite of simulation tools as an integral component. Similarly, the use of fire arcs to visualize the portions of space that is crisscrossed or targeted by artillery rounds – and therefore unsafe for passage – is a feature that has been implemented by the AAcuity® PC-IG in response to the needs of various clients. Figure 25 displays an example of the use of the aforementioned symbols in a battlefield. The friendly entities are affixed with blue colored

symbols (circles) while those of the enemy are affixed red symbols (diamonds far right). Note that, one of the friendly entities is shown firing at the enemy, with the parabolic arc taken by the round updated in real-time to coincide with its flight path.

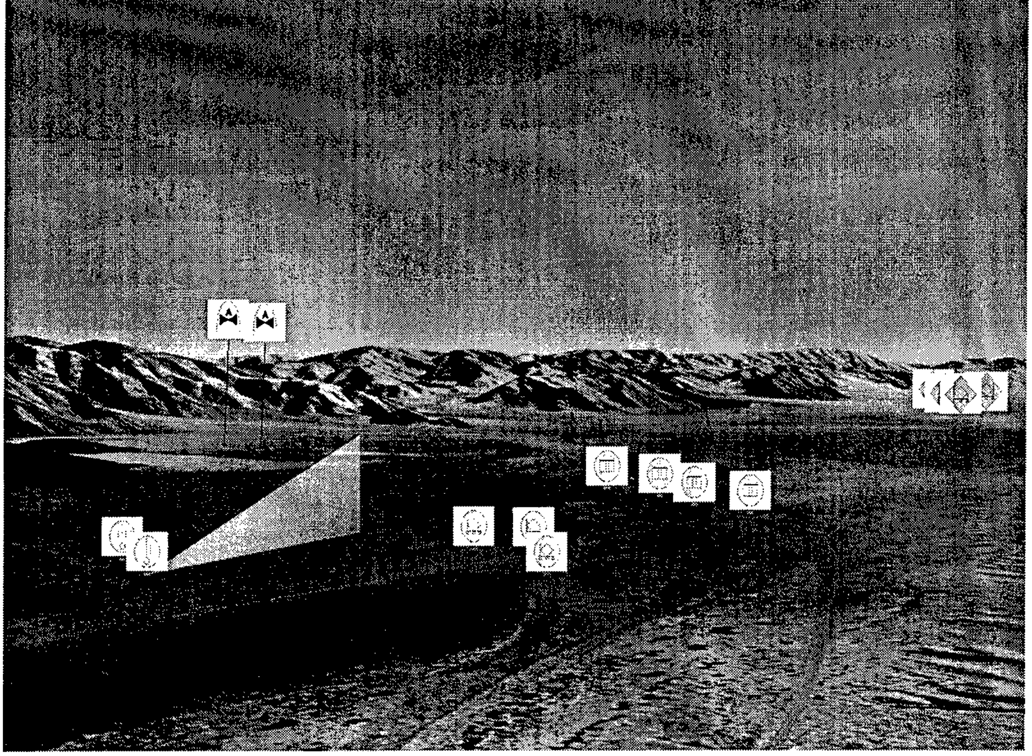

Figure 25. Illustration of a battlefield displaying the use of symbols in the AAcuity® PC-IG for representing entities and fire arcs that trace the flight path of artillery rounds.

The use of visual cues can be extended by the AAcuity® PC-IG to suitably display the degree of threat posed by a hostile entity. Some of the models that have been researched by SDS in the past include translucent threat cones and umbrellas. The tip of a threat cone is anchored on a hostile entity and the volume of the cone at any instance contains the space whose likelihood of being targeted by the entity's weapons is high and imminent. Note that, such a threat cone contains a confined volume of space that is under imminent threat and which can be expected to change frequently with time. For instance, the threat cone associated with a tank at any given time is the cone whose axis runs along the barrel of its main gun. Naturally, this cone can change as the tank changes its aspect or turns its turret. Similarly, a threat umbrella is centered on a hostile entity and the space underneath the umbrella is within the range of the entity's weapons. However, these models suffer from certain deficiencies. Foremost amongst them is that, the cones or umbrellas of multiple entities in close proximity to each other often appear far too cluttered to offer any useful visual information. Furthermore, a large number of weapon systems in a simulation often have long kill ranges. This frequently results in the visual cones or umbrellas of multiple adversaries enveloping the observer, making it difficult to ascertain which entities pose threats and which ones do not. For the previously stated reasons, it is best to represent the threat and its degree using colored symbols ascribed to the respective hostile entities. For instance, the following color band (Figure 26) displays five levels of threat.

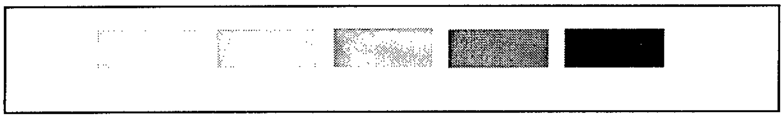

Figure 26. Displays the prospective levels of threats using.

Figure 27 displays the prospective forms of threat symbols that may be implemented by the AAcuity® PC-IG to indicate the level of threat ascribed to a hostile entity. The triangular flag on the extreme right indicates the highest level of threat while the one to its left indicates a medium level of threat.

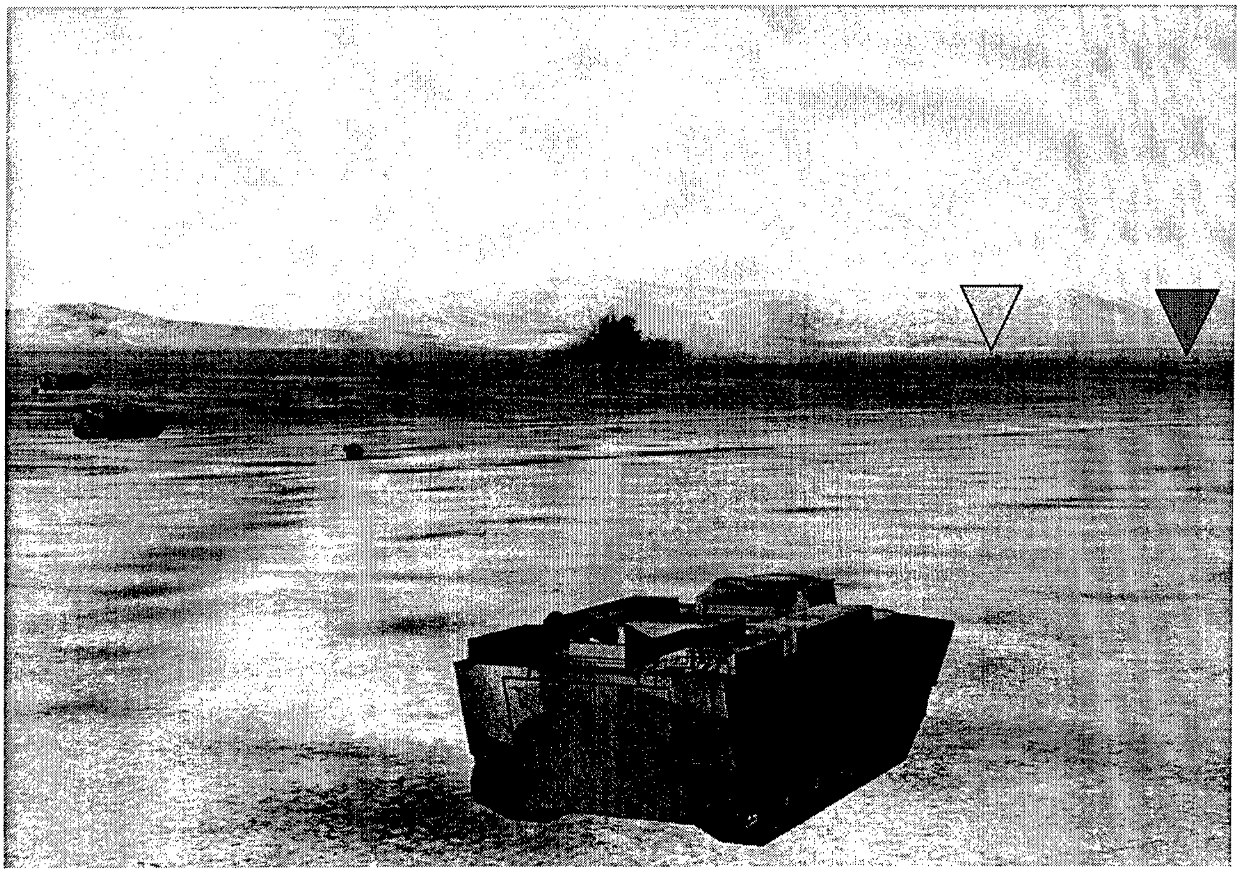

Figure 27. Illustration of the threat level of hostile entities with respect to the armored personnel carrier in the foreground displayed using colored flags.

Visualizing Formations

Visualizing formations and projecting their trajectories on a battlefield is an important skill that is critical to determining the significant objectives of the adversary. Battlefields can often be cluttered with heterogeneous masses of seemingly unrelated or independent entities numbering in the hundreds, if not thousands. Under these circumstances, visualizing groups or formations from the cluttered mass of their constituent entities is a substantial challenge. For this purpose, simulations using scripted scenarios with entities in pre-configured formations can provide suitable feedback and train users to visualize this skill. However, in non-scripted simulations such information has to be either disseminated prior to the exercise or visually ascertained by an expert. Hence, to facilitate training in those environments the development and use of a lightweight expert system may be beneficial. Furthermore, a significant benefit accrued from modeling cognitive processes is that, its accuracy can be progressively refined using empirical data, and that in turn can be used to train its related human skill. SDS has identified two preliminary techniques that may serve as candidates to achieve this objective. The first is the use of Bayesian models for statistically inferring the constitution of formations based on their degree of correlation to various entities. Before we state the criteria that may be used for correlating entities to formations, we define the center of gravity of a formation.

Let $E = \{e_1, e_2, \ldots, e_N\}$ be a set of entities in a formation with the position of entity e_i on the *x-z* plane of the right-handed 3D coordinate system being $p(e_i) = \{x_i, z_i\}$. Then the center of gravity of the formation is given by the position $\{x_G, z_G\}$, where $x_G = (x_1 + x_2 + \ldots + x_N)/N$ and $z_G = (z_1 + z_2 + \ldots + z_N)/N$. Note that the center of gravity is simply a non-weighted average of the positions of the entities. Figure 28 displays the center of gravity using a formation comprised of

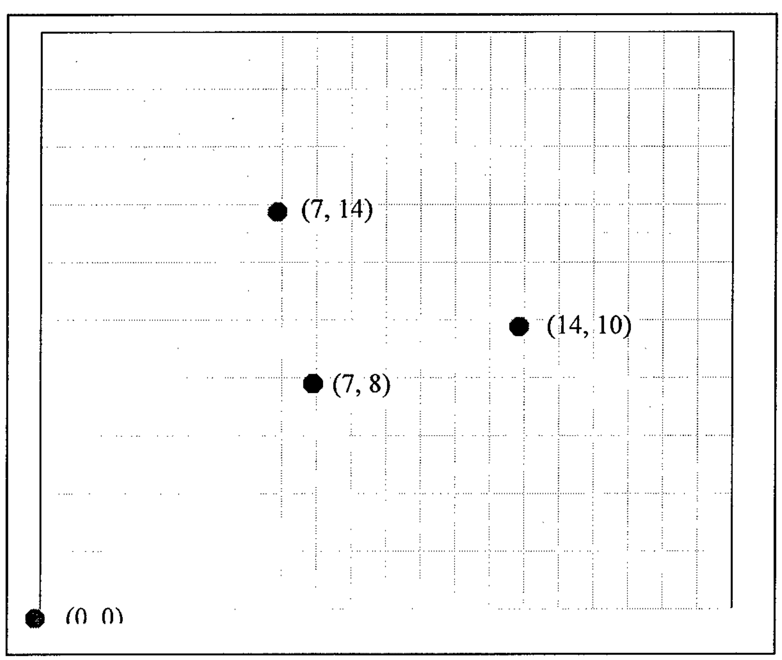

Figure 28. Grid displaying three entities colored brown (0, 0, 7, 14 & 14, 10) and the center of gravity of their formation in blue.

three brown-colored entities at the locations (0, 0), (7, 14) and (14, 10). The center of gravity for this formation of three entities is given by the dot at the location (8, 9).

We note that the center of gravity can be used as a distinct representative of its formation that provides a general sense of the position, speed, and heading of the formation by quantitatively averaging those parameters obtained for the various entities constituting it. Furthermore, we shall define the center of gravity of a formation relative to the point denoting the smallest x and z values for any entity in that formation. That point is denoted as the origin with coordinates (0, 0). This assumption is necessary to ensure that, the center of gravity of a formation that is in motion does not change over time as long as the relative positions of its constituent entities remain invariant. Using this definition, we state the following set of criteria that may be used for determining the correlation of entities to formations.

a. Proximity of an entity to the center of gravity of a formation.
b. Proximity of the speed of an entity to the speed of the center of gravity of its group.
c. Proximity of the direction of movement of an entity to the direction of movement of the center of gravity of its group.

The intuitive reasoning that motivates the choice of the aforementioned set of criteria is as follows. An entity is likely to be a member of a formation, if that entity's relative position with respect to (the center of gravity of) the formation is invariant for each tactical configuration of that formation, and/or its speed consistently matches the speed of (the center of gravity of) a formation, and/or its heading is fairly consistent with (the center of gravity of) the formation. Furthermore, we also want to show that if and when the position, speed or heading of the center of gravity of the formation changes there is a corresponding change in the position, speed and heading respectively of that entity. We start with the criterion that measures the proximity of an entity to the center of gravity of a formation, and later show that this criterion is substitutable by any of the other criteria. We then make the following set of intuitive observations.

Observation (i)

If a formation changes its configuration – and most likely its center of gravity – to execute a tactical goal, we can expect that, an entity within the formation has changed its position with respect to the center of gravity of the formation to execute a sub-task. An example of this scenario is where a platoon of tanks breaks up formation to flank an adversary and thereby changes its center of gravity. Then, a tank in one of the flanking units is likely to be at a distance from the center of gravity of its parent formation that is a function of the position of the center of gravity itself from the origin.

Figure 29 illustrates the scenario mentioned in observation (i) in a limited setting using a formation comprised of two tanks. The two outlined circles show the positions of the tank in a previous point in time and the solid circles (4, 9 and 16, 7) the current positions of the tanks. The corresponding outlined and circles represent the center of gravities of the formation

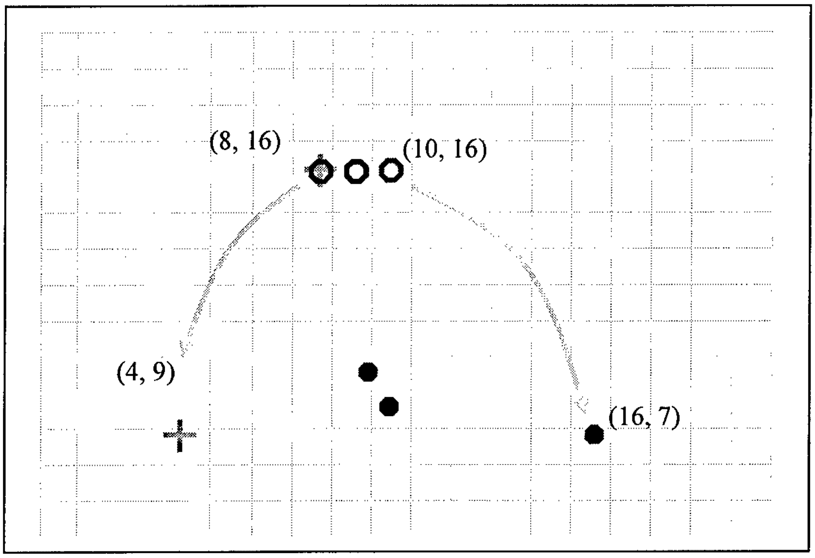

Figure 29. Grid displaying the movement of two entities. The top outlined circles (8, 16 & 10, 16) show their previous positions, and the solid circles (4, 9 and 16, 7) their current positions.

at the previous point and current point in time respectively. Note that the origin in the past is centered on the entity at (8, 16), and the origin at the current point in time is centered at the coordinates (4, 7), both designated by crosses. The arcs tipped with arrows display the paths followed by the tanks. Then, we observe that the center of gravity of the formation is initially at distance 1 from the origin while the entity on the right is at a distance of 1 from the center of gravity. Subsequently, the center of gravity of the formation is at distance $\sqrt{37}$ from the origin while the entity on the right is at a distance of $\sqrt{37}$ from the center of gravity.

Unlike the previous example, an entity that is part of a formation may not necessarily change its distance from the center of gravity of the formation significantly whenever the center of gravity itself changes significantly or vice-versa. For instance, a set of tanks in an armored formation may be designated to mount a frontal assault while other tanks on the flanks of the unit execute a pincer movement. In that case, the change in distance between tanks in the center of the formation from the center of gravity of the formation is unlikely to be very significant. For example, Figure 30 displays a formation of three entities at the locations (8, 16), (9, 17) and (10, 16), with their center of gravity shown by the outlined circle. While the two entities on the flanks execute a pincer movement the tank in the center approached head on towards an adversary located on the southern end of the grid. Note from the final positions of the entities that, the change in distance of the entity in the center of the formation from the center of gravity is far lesser than that of its counterparts. However, such an entity is likely to retain its relative position within a formation and therefore, the distance of the entity from the center of gravity of its formation is always likely to be conservative. Conversely, entities on the flanks are likely to experience far greater changes in their distance from the center of gravity of their formations. From the preceding discussion we observe the following final item.

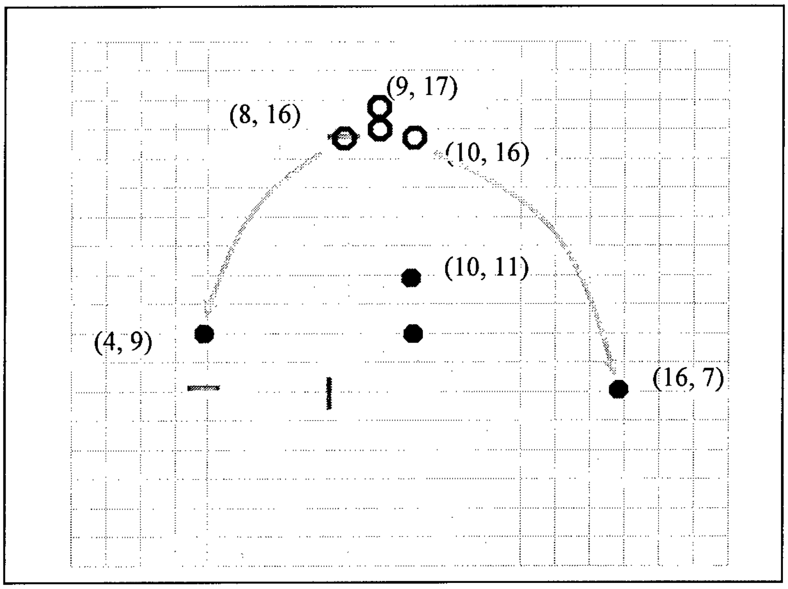

Figure 30. Grid displaying the movement of three entities. The outlined circles (8, 6, 9, 17 & 10, 16) show their previous positions, and the solid circles their current positions.

Observation (ii)

If a formation does not change its configuration (and therefore its center of gravity) we can expect an entity within the formation to retain its position with respect to the center of gravity of the configuration. This is a fairly trivial observation.

Observation (iii)

If an entity's mean distance from its formation's center of gravity is $f(d)$ when the formation's center of gravity is at distance d from its origin, then the expected value of the entity's distance from its formation's center of gravity when the formation's center of gravity is at distance d' from the origin, is $f(d')$ if d and d' are relatively close to each other. This is based on the assumption that, an entity within a formation can be expected to execute the same set of tactics assigned to it in a plan in future iterations of that plan, and thus maintain the same set of positions relative to the formation to execute its assigned set of tactics. Furthermore, by extension of this argument to all entities in a formation, we may expect the formation itself to have a configuration similar to that it used to overcome such resistance in the past, and therefore experience changes to its center of gravity similar to that in the past.

Note that, all the aforementioned observations state expectations of the events only and therefore those with a high probability of occurrence, but not with certainty. Using the aforementioned observations, we now define the mathematical framework necessary to quantitatively measure these criteria.

We may also expect the function $f(d)$ defining an entity's mean distance from its formation's center of gravity where d is the distance of the formation's center of gravity from the origin to be different for values of d lying in different intervals. This is based on the assumption

that an entity's position with respect to its formation is likely to be unique to the specific tactic employed by its formation, which in turn is executed using a specific configuration with a unique center of gravity. For this reason, it would be intuitive to divide the sample space of all distances of the center of gravity of a formation from its origin into n intervals each of length d, d a positive integer, where each interval bounds the formation's center of gravity with specific configuration. Thus we have intervals of the form $[0, d)$, $[d, 2d)$, $[2d, 3d)$, ... $[(n-1)d, nd)$. For each change in the center of gravity of the formation within the interval $[xd, (x+1)d)$, $0 \leq x \leq (n-1)$, we plot the frequency of the changes in distance of an entity from the center of gravity of its hypothesized formation.

Figure 31 illustrates a case where the frequency of changes in distance of an entity from the center of gravity of its hypothesized formation is plotted as a function of distance ranging between say 0 to 10, 10 – 20, 20 – 30 meters and so on. Let us assume that this plot corresponds

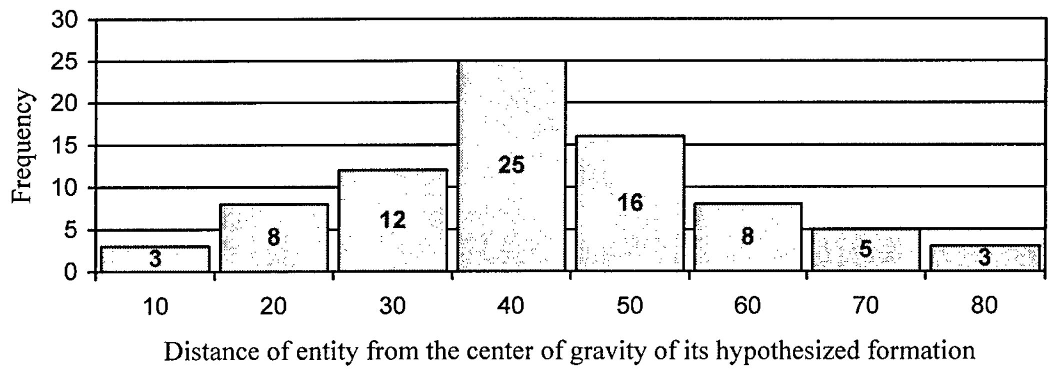

Figure 31. Plot of the frequency of the observed distances of an entity from the center of gravity of its hypothesized formation.

to changes in the center of gravity of the formation in the range of say 10 – 20 meters observed over 80 iterations. Let the mean value of this frequency distribution be υ, which in the case of the example equals 37.75 meters. Then, the standard deviation probability distribution is given by the value,

$$\sigma = \sqrt{(1/N\,(\textstyle\sum_{i=1}^{N}(x_i - \upsilon)^2)}$$

In the case of the example $\sigma = 23.02$. We know that 68% fall within one standard deviation of the mean, 95% fall within two standard deviation of the mean, and 99.7% fall within three standard deviation from the mean. Thus, σ gives us a good indication of the frequency of events close to the mean. The lower the value of σ, the higher the number of events closer to the mean and vice-versa. Intuitively then, a lower value of σ indicates the likely existence of dependency between an entity and its hypothesized formation.

Rejected Distance Observation (iv)

Note that, each value of σ as defined in observation (iii) is evaluated for a corresponding distance of the center of that formation from its origin within an interval of the form $[xd, (x + 1)d)$, where $0 \leq x \leq (n - 1)$. Hence, based on observation (iii), it would be intuitive to reject an entity from inclusion into a hypothesized formation if the value of σ for that entity is significantly different from the average value of σ over all entities in that formation corresponding to a majority of intervals.

Change Formation Observation (v)

Once an entity has been rejected from its hypothesized formation, we select an alternate formation into which it may qualify, or create a new formation comprised of that entity alone. The formation into which the entity qualifies for membership is decided using a function comprised of the weighted sum of factors that include proximity to the candidate formation's center of gravity, velocity and directional heading. This is similar to the technique applied in Genetic algorithms for maximizing or minimizing the objective function.

Spaced and Direction Observation (vi)

Up to this time we have used the criterion of "distance" to highlight all observations, but we can easily substitute criteria such as speed and directional heading to achieve similar results. For instance, we may measure the correspondence between values of pairs of metrics such as the speed of an entity and the corresponding speed of the center of gravity of its hypothesized formation. Similarly, we may measure the correspondence between values of the directional heading of an entity and the corresponding directional heading of the center of gravity of its hypothesized formation.

Using observations (i) through (vi), we can state the algorithm for identifying the inclusion of an entity into a hypothesized formation as given in Figure 32. Let $c_i(e)$ define the value being for entity e and $c_i(F)$ the value of the center of gravity of the hypothesized formation F containing e, in iteration i using criterion c. Let $c(F)$ denote the entire sample space of potential values for the formation F using criterion c.

```
while (simulation continues) do
{
    Partition the likely values of c(F) into n partitions.

    for each entity e in F do
    {
        for partition i ← 1 to n do
        {
            // Compute the new mean for c(e)
            υ ← (υ x (i – 1) + c_i(e))/i;

            // Compute the new standard deviation for c(e)
            σ ← √(1/i (Σ_{k=1}^{i} (c_i(e) - υ)^2)

            // Computes the average of the standard deviation for entity e
            sigma[e] ← ((i – 1) x sigma[e] + σ)/i;
        }
    }

    // Compute the average of the standard deviation for all entities and store it in
sigmaF
    for each entity e in F do
    {
        if sigmaF ← sigmaF + sigma[e];
        mismatch[e] ← 0;
    }
    sigmaF ← sigmaF/|F|;

    // Determine entities whose standard deviations exceed the average for their
formation by a    // threshold value T.  Count the number of such cases for e using the
variable mismatch[e]
    for each entity e in F do
    {
        if |sigma[e] – sigmaF[e]| > T then
            mismatch[e] ← mismatch[e] + 1;
    }

    // If number of mismatches exceeds the number of criteria then we should
reject the
    // possibility of e being a member of the formation F.
    if mismatch[e] > |c| then
        reject e from F;
}
```

Figure 32. Algorithm to identifying the inclusion of an entity into a hypothesized formation.

Visualizing Over Time

Any battlefield plan requires a minimum amount of time for its execution. Therefore, during the formulation of any plan, its planners must carefully evaluate the amount of time available for its execution to ensure that it does not exceed the available time. If that is true, then it must be discarded in favor of suitable alternatives. Hence, to enable battlefield planners to formulate a viable plan, it is crucial that they have reasonably reliable knowledge of the estimated time of arrival (ETA) of enemy forces at any location of interest. Such a location may be a point where engagement is to be initiated or some element of the plan is to commence. For this reason, the need to visualize the position of an entity or a formation over time is an important skill vital to the effectiveness of warfighters.

While the path that will be taken by an entity or a formation can never be predicted with certainty, we can estimate the bounds within which their positions may be expected to lie. Some of the criteria that can be used to make that determination are as follows.

a. The speed of the entity or the formation

b. The obstacles that surround the entity or formation that necessitate changes in heading

c. The location of vital assets that may be targeted by the entity or the formation and therefore influences its path. For instance supply depots, airfields, railway junctions, power stations, TV and radio stations are very likely to be prioritized for capture by the enemy even if they are not the primary targets.

d. The location of defensive forces that may be targeted for neutralization.

e. The presence of highways and roads that facilitate the mobility of non-tracked vehicles.

This is a problem that may be represented as a least-cost path problem discussed in a preceding section. In this representation edges on the underlying wire frame of the topography constituting obstacles are assigned weights with commensurately large values. Similarly the edges on the wire frame lying underneath a highway or road are assigned very low costs. Finally, the costs of the edges beneath the terrain leading up to assets are given progressively lower costs. The exact cost values may have to be derived after some research with the assistance of subject matter experts to faithfully simulate the desirability of an asset at variable distances. The higher the desirability, the lower the cost.

Using such a model, the least cost path from the position of an enemy entity or formation to the position of a defensive force or asset can be easily derived using any of the previously discussed algorithms, such as those by Dijkstra and Floyd. Once the most economical route has been derived, the position of the entity or formation is a function of time and its speed projected along that route.

Note that for a given entity or formation, we probably need to choose a multiple set of assets within a fixed distance *d* and compute the most economical paths to each of those assets to prevent restricting the entity or formation to unrealistically targeting only a specific asset.

Miscellaneous Visualization Skills

There are numerous other visualization skills that can be trained by mostly using the existing functionality of the SDS AAcuity® PC-IG and NEXWARS. Some of the more notable ones are as follows.

- Given a 3D view of a formation of entities in the distance, can the subjects estimate the time in which the leading elements of the formation will reach a specific point in the formation's path that is of interest to the subject? That point could be the periphery of the subject's predefined engagement zone or a marker to designate the point at which the subject launches a well-defined set of actions such as calling in air/artillery support, initiating a withdrawal or planned retreat. Note that the entities may be a heterogeneous collection of troops and vehicles. This can train the subject's ability to associate proportion with distance and the rate of change of proportion with speed. The use of laser rangefinders incorporated into NEXWARS in conjunction with stopwatches will permit the subject to obtain the correct answer to each scenario displayed in an iteration of the training process.

- Given a 3D Out-the-Window (OTW) view from a moving vehicle, can a subject estimate the time in which they will reach a specific point in their path (not necessarily an endpoint) that is of interest to the subject? The destination could be a point designated on a 2D map or visually identified in fair weather affording visibility over great distances. That point could be the periphery of an area that is known to be within the range of enemy fire, or the boundary of a holding area. The path may encompass heterogeneous terrain that poses different challenges to the vehicles' progress. Thus, the subject may have to factor in varying rates of progress over each patch of terrain having a unique topography to arrive at an accurate estimation. For instance, the vehicle within which the subject operates may be an amphibious vehicle that has to traverse across some a flat section of terrain followed by some undulating hills, and finally to a designated location across a river with a width of 200 ft. Furthermore, weather may be changed to insert a greater number of variables to be taken into consideration by the subject to derive the ETA accurately. For instance, rain or fog may be inserted into the scenario to reduce visibility, reduce speed and thus change the criteria for obtaining an ETA.

- Given a moving formation's location and heading on a 2D map, can a subject estimate the path to be taken to intercept or join up with that formation in the least amount of time and the time taken to do so correctly. This task requires the subject to not only visualize the formation's movement, but also their own with respect to time. Note that, the target formation may not necessarily be the enemy, but could be a formation of friendly forces to be extended support in the least amount of time. This is a situation where above-real-time training (ARTT) may be valuable to the subject in visualizing motion accurately over time.

- Given an objective and a timetable for reaching that objective, can the subject quickly plan alternatives to meet its schedule in the event the enemy threatens to disrupt its original plans? For

instance, if an enemy force threatens the subject's progress, should the subject engage the enemy force or should the subject try to find an alternative route for reaching its objective? Both alternatives may be time consuming, but one may be more economical than the other upon consideration of the times required for engaging the enemy while pursuing the original course as opposed to the cost of re-routing. Can the subject determine if either alternative is compliant with the original schedule and pursue the most preferable one?

• Given a mission, can a subject identify anomalies in the execution of the mission? For instance, if entities/formations assigned to different objectives are permuted with respect to their original assignments, can the subject notice the difference? This is a problem ascribed to the limitations of short-term memory that has been acutely observed in exercises (Hutchins and Kowalski, 1993; Hutchins, Morrison & Kelly, 1993).

Training Developments

This section describes how the training will apply technology to address each of the visualization skills previously identified. For all training the SDS NEXWARS shall feature a unique property-page interface, and based upon the mutually exclusive page selected by the trainee, NEXWARS can identify the skill that is being trained. Thereupon, NEXWARS can perform all necessary context-sensitive initialization and operations. One of the features necessary for implementing the following training procedure is the ability to load training scenarios with multiple entities at selected locations on a desired terrain database.

Visualizing 2D to 3D Terrain Correlation

In the preceding sections we discussed the technologies to be embodied by the AAcuity® PC-IG to display a given terrain in either of two forms, 2D or 3D. Furthermore, we showed how a 2D contour can be partially or wholly morphed into a 3D terrain. With this capability, a subject may be presented with two PC-IGs, one displaying a section of a 2D contour map with no or partial morphing to its 3D counterpart, and the other displaying an isometric view of a related section of 3D terrain. This perspective view would provide an inclination angle based on the trainee's duty position (i.e., if a dismounted Soldier then an egocentric perspective view from that angle). Presumably, a subject's ability to visualize 3D topography from the 2D contours is determined by their ability to correlate the two views. The trainee may use an iterative approach to train this skill, with an iteration comprised of the steps (a) through (c) below. The iterations are however preceded by the following initialization.

First, configure the broadcast reception ports of the pair of AAcuity® PC-IGs to the unique transmission ports of a corresponding pair of NEXWARS hosts. This establishes a one-to-one correspondence between the NEXWARS hosts and the AAcuity® PC-IGs. Finally, load the same terrain database for each AAcuity® PC-IG.

a. The trainee is presented with a 2D contour map and multiple 3D perspective views, one of which corresponds to the 2D view. The trainee has X amount of time to choose the correct 3D perspective. If the answer is incorrect, or the trainee fails to make the choice within

the allotted time, the 2D view step morphs into a 3D perspective view, with a low inclination angle.

b. The trainee is then allowed to make a choice again. If the answer is incorrect, or not within the allotted time, the 2D view is step morphed into the next 3D perspective view.

c. If the trainee is unable to choose the correct answer in a certain number of steps, (see Note below) then after all steps have been exhausted, the trainee is presented with the correct answer and the 2D view is morphed in slow-motion into the 3D perspective view.

The maximum number of stepwise changes to the inclination must be less than the 3D perspective views from which to choose. For example, if the 3D perspective view is with an inclination angle of -15° and each step morphing is -15° then there will be five steps required to transition from the top-down orthographic view to the perspective view. Thus, the number of choices should be about 10 to reduce the possibility that the trainee will select the correct choice by chance.

This process is continued until the trainee is able to determine the correct answer. The number of morphing steps needed to obtain the correct answer judges the performance. An automated scoring system is suggested based on this principle.

There should be multiple levels of difficulty of the exercise. The easiest level should consist of terrain choices that are significantly different from the correct answer. These choices should become progressively similar to the correct answer. An additional level of complexity can be incorporated through an orientation mismatch between the 2D contour map and the egocentric perspective views of the terrain. The mismatch should be progressively increased to train mental rotation skills of the trainee. Before proceeding to the next difficulty level, the trainee should correctly answer a number of trials with similar difficulty level correctly.

Visualizing Optimal Cost for Terrain Traversal

This exercise is expected to train the skill of determining the optimal path (minimal cost) between two points on a terrain using a 2D topographic map. To do that, the morphing capability of NEXWARS from 2D to 3D would be used. A pre-training session would be conducted to explain to the trainees how the cost of the path would be determined. This skill can be trained by using an iterative approach, with an iteration comprised of the following steps.

a. The NEXWARS presents two random points P_1 and P_2 on a 2D contour map distance d apart and instructs the AAcuity® PC-IG to display them to the subject.

b. Using an input device or pointer, the subject plots a sequence of waypoints on the AAcuity® PC-IG between P_1 and P_2 to create the path visualized by the subject to be the most economical one between those two points.

c. The NEXWARS calculates the cost of the path described by the trainee and displays its cost.

e. The NEXWARS derives the most economical path and displays it with its cost normalized with respect to the trainee-defined path.

e. If the total cost of the trainee's selected path is more than the optimal cost then the 2D view is step-morphed into a 3D perspective view. The trainee now re-plots the path between the

two points; this process continues in an iterative fashion until the trainee is able to determine a path within certain limits of the optimal cost.

f. If the trainee fails to meet the standard within the allotted number of trials, the optimal path and the costs at predetermined waypoints are displayed. Again, the trainee has an ability to see the detailed contribution of the terrain features for each segment by clicking on the waypoints.

Another feedback mechanism available to the trainee is to choose any segment of the optimal path and view the terrain feature contributions to the cost for that segment.

A measure of performance can be the number of step morphs required to reach the optimal cost. When an appropriate proficiency level is achieved with that degree of complexity (i.e., the number of parameters in the cost function) then the trainee will be allowed to progress to the next level. One way to increase complexity is to increase the number of different terrain features between the two points.

Visualizing Line of Sight

SDS proposes a fairly unique solution to enable subjects to rapidly visualize line of sight between any set of points to the entire region surrounding it. This skill can be trained using the following approach.

a. The AAcuity® PC-IG displays a 2D contour map to the trainee with a point P representing the trainee's viewing position. A number of points on the map are indicated as well. The trainee's task is to choose which of the points fall within the line of sight of Point P.

b. If the trainee is unable to answer correctly, the 2D contour map step-morphs into a 3D perspective map from the perspective of point P. This step-morphing is continued until the view becomes that of the perspective view of the trainee (i.e., an egocentric view of a dismounted Soldier). If the trainee is unable to answer correctly within the allotted number of morphing steps, an omni-directional light source at point P illuminates the areas of the terrain that are in the line of sight. Those that are not in the LOS remain shadowed. Further, the points that were presented to the trainee at the beginning of the exercise are also displayed.

A number of sessions with similar complexity level are practiced before moving to the next level of complexity. Increasing levels of complexity are then practiced, each incorporating more complex terrain features.

Visualizing Distance

As described previously, the trainee may instruct the extended AAcuity® PC-IG to generate posts to assist them in visualizing the distance to an entity. To train this skill, the trainee may use an iterative approach, with an iteration comprised of the following steps.

a. The AAcuity® PC-IG displays a scenario with at least one entity visible to the observer.

b. The trainee estimates the distance to any visible entity.

c. The trainee instructs the AAcuity® PC-IG to generate posts to assist in their estimation.

d. The trainee inserts their estimated value into an edit box provided by NEXWARS in the property-page designated for this skill.

e. The trainee checks the accuracy of their estimation by directly lasing the target or selecting it using the green hand. Either of those actions prompts the AAcuity® PC-IG to display the distance from the observer to the lased or selected target.

Repetition of steps (a) through (e) can be used to gradually enhance the ability of the trainee to judge distances with visual assistance. Upon reaching a certain threshold of accuracy, step (c) in the process can be eliminated, and replaced by the trainee's visualization capacity to mentally recreate such posts in the scenario and estimate distances accordingly. Step (d) allows NEXWARS to maintain a running count of the percentage deviation of the trainee's estimations from their true values, and provide that to the trainee as feedback. If the deviations are observed to be large, then successive iterations of steps (a) through (e) can be performed using scenarios where the distance of the entities are closer to the observer.

Visualizing Dispersion

As described previously, the trainee may instruct the extended AAcuity® PC-IG to overlay a protractor to assist them in visualizing the dispersion between any two entities in a scenario. To train this skill, the trainee may use an iterative approach, with an iteration comprised of the following steps.

a. The AAcuity® PC-IG displays a scenario with at least two entities visible to the observer.

b. The trainee estimates the dispersion between any two visible entities.

c. The trainee instructs the AAcuity® PC-IG to overlay a protractor to assist them in their estimation.

d. The trainee inserts their estimated value into an edit box provided by NEXWARS in the property-page designated for this skill.

e. If his response exceeds the error limits then the protractor's rays are increased by a certain length to help the trainee better visualize the angle of separation. This process is continued until the trainee provides an acceptable answer.

The number of steps required to achieve the correct answer is a measure of trainee performance. Once the trainee is skilled to estimate the dispersion using a minimum size of the 'protractor', this visualization aid should then be removed and the trainee tested for accuracy. Distance between/from the entities can be the complexity variables.

Visualizing Threat From Enemy Signature

As previously described, the capabilities of the AAcuity® PC-IG can be extended to ensure that the size and form of the dust trails generated by formations are commensurate to the size of the individual entities and their number in the formation generating them. Hence, the

trainee may then use an iterative approach to train their ability to visualize threats from their signatures, with an iteration comprised of the following steps.

a. The AAcuity® PC-IG displays a scenario with a formation comprised of multiple entities generating a visible dust trail at a distance where the entities are invisible to the observer.

b. The trainee estimates the number of entities in the formation.

c. The trainee inserts their estimated value into an edit box provided by NEXWARS in the property-page designated for this skill.

d. The trainee may check the accuracy of their estimate by directly referring to the property page on NEXWARS that displays the number of entities in an exercise and their details.

Repetition of steps (a) through (d) can be used to gradually enhance the ability of the trainee to judge the number of entities comprising a formation generating a visible dust trail. Step (c) allows NEXWARS to maintain a running count of the percentage deviation of the trainee's estimations from their true values, and provide that to the trainee as feedback.

Complexity will be built into the system by the ability to increase or decrease the distances between entities, changing wind directions and trainee views, for example to influence the discernment of the individual dust trails. The measures of performance will include the accuracy of the estimate and the time taken to respond.

Visualizing Trajectory

As previously described, the SDS NEXWARS is capable of maintaining the history of the position of entities and estimating their likely positions in the future based on their trajectory. Using this capability, subjects may use an iterative approach to train their ability to visualize the trajectory and thus the future positions of any desired entity. Each such iteration is then comprised of the following steps.

a. The trainee will be presented with a scenario in which a single entity is moving with a constant speed and direction. The view will be an egocentric view of a 'dismounted Soldier'. The scenario runs for awhile and then stops; the trainee is then asked to input the projected position of the entity at time *t* using the green hand pointer based upon his estimate of the trajectory.

b. The inclination angle should be the complexity parameter within each training scenario and hence the view should 'step-morph' into a 2D view as easiest view of the scenario. This step-morphing would occur when the trainee's response exceeds the maximum allowable error in position.

c. The other training parameter within a specific complexity level would be the 'ghost views' of previous positions. The most complex would be no 'ghost view' and least challenging would be a certain number of 'ghost views' to help reconstruct the trajectory.

The next level of complexity would be a path with a constant curvature and constant speed. The scenario would be made more complex by having multiple entities, thus requiring the trainee to maintain knowledge of the motion of all these entities and then project the position of a computer selected random entity. The number of morphing steps required by the trainee to determine an acceptable answer measures performance.

To provide visual feedback to the trainee at the end of the exercise, the trajectory would be presented dynamically as a series of ghost views left behind at certain intervals by the moving entity. To further augment the trainee's visual projection skills, a moving arc at a distance δ centered at the entity also will be presented. Note that the value of δ is proportional to the speed of the entity.

Visualizing and Prioritizing Threat

Because this skill is a complex skill comprised of several of the other previously trained skills, it will be taught in two parts.

Part 1

a. The AAcuity® PC-IG displays a scenario comprised of a heterogeneous collection of enemy entities at varying distances from the observer.

b. The trainee then selects on the property page in NEXWARS corresponding to this skill, the threat level for which entities are to be identified.

c. Using the green hand pointer, the trainee then selects the entities at the previously selected threat level.

d. Trainee repeats step (b) for a new threat level and the appropriate set of entities for that threat level.

e. The SDS NEXWARS compares the choices of the trainee with its computed analysis of the threats posed by the various entities. It then displays its analysis of threats to the trainee on the AAcuity® PC-IG. If the percentage of correct choices by the trainee exceeds a specified threshold the number of entities in the scenario is increased and/or their placement altered significantly in the scenario loaded for the next iteration. On the other hand, if that percentage is below that threshold, the number of entities in the scenario is reduced and the scenario repeated in the next iteration.

Part 2

Once the trainee is experienced in identifying different categories of threats based upon their position and the effectiveness of their weapons, the training proceeds to Part Two.

This skill level is comprised of threat level, terrain appreciation, line of sight, and projected trajectories and positions in a dynamic environment.

The training in this segment will proceed as follows:

a. A single entity approaches a vulnerable point (VP) with a constant speed. The trainee identifies the entity (i.e., the effective range of its weapon), determines its closure rate, (using the laser range finder) and estimates the time/position when it could become a threat to the vulnerable point and inputs the estimated position using a pointer. NEXWARS determines the accuracy and reaction time. If within acceptable limits, the trainee progresses to the next complexity level.

b. Having two entities in the scenario approaching the VP from two different directions would increase the complexity level. Other parameters to increase complexity within this level would be speed, weapons range, distance from vulnerable point, direction and trajectory.

c. The scenarios would incorporate terrain features as well. Thus the lowest terrain complexity would be flat terrain while complex terrain feature would be, for example, a hill closer to the VP with an entity hidden behind it.

d. Also the element of entity trajectory projection could be incorporated in a manner that some entities may be perceived as moving toward the VP, but in actuality their trajectory would be such that they would miss the VP if allowed to continue. Thus, these entities could be determined as threats if the trainee projects their trajectories inaccurately. An additional layer of skill may be trained by adding time compression, or ARTT.

Visualizing Formations

As previously described, the SDS NEXWARS will be capable of estimating the composition of formations over time. Using this feature, subjects may use an iterative approach to train their ability to visualize formations with an iteration comprised of the following steps.

a. The AAcuity® PC-IG displays a scenario comprised of a heterogeneous collection of enemy entities with the observer having an orthographic view of the collection from a suitably high altitude. The entities are displayed using 2525B symbols to ensure that they are visible to the observer. The collection of entities may contain one or more formations, and independent entities.

b. The trainee then selects on the property page in NEXWARS corresponding to this skill, the formation (identified by a number) for which entities are to be identified as members.

c. Using the green hand pointer, the trainee then selects the entities visualized to be members of the previously selected formation.

d. The SDS NEXWARS performs its own analysis of the entities that comprise a formation and displays those results using color-coded symbols on the AAcuity® PC-IG such that, entities that are members of the same formation are assigned the same color code. Finally, NEXWARS compares its results with the selection of the trainee. If the percentage of entities correctly associated by the trainee with their respective formations exceeds a specified threshold a new scenario is loaded in the next iteration. On the other hand, if that percentage is below that threshold, AAcuity® PC-IG removes its color-coded symbols and repeats the scenario with the same collection of entities albeit at a different location on the database.

Visualizing Over Time

As previously discussed, the SDS NEXWARS will be capable of estimating and displaying the likely position of an entity or formation over time using the least-cost path algorithm. Using this feature, subjects may use an iterative approach to train their ability to visualize dynamics over time with an iteration comprised of the following steps.

a. The AAcuity® PC-IG displays a scenario comprised of a heterogeneous collection of enemy entities with the observer having an orthographic view of the collection from a suitably

high altitude. The entities are all in a state of motion. All relevant details such as roads and obstacles are suitably displayed in the orthographic view to the trainee.

b. Using a pointer, the trainee selects an entity whose position is to be visualized following a period of time t.

c. The trainee then selects a location on the terrain where the entity is expected to be following time t.

d. SDS NEXWARS estimates and displays its computed results for the likely position of that entity following time t using the least-cost path algorithm.

e. The trainee then decides if they wish to wait for time t to verify their choice or allow NEXWARS to be the judge. If the trainee chooses the latter option, then the deviation of their choice from the position computed by NEXWARS is noted. On the other hand, if they choose the former option, the deviation of their choice from the actual position of that entity a time t later is computed. If the deviation is larger than a specified threshold then step (a) is repeated with a new scenario with a reduced value of t.

Future Work

The results obtained in Phase I of this STTR provide a reasonable basis for Phase II development of a training system to address the identified set of visualization skills. For this purpose SDS has already outlined a set of technical objectives to be accomplished, the high-level architecture of the training system and some key training components.

Phase II Technical Objectives

1. Design suitable methods in the AAcuity® PC-IG to morph and display terrain in forms ranging from 2D contours to their equivalent fully textured 3D imagery in graduated steps. This objective is anticipated to encompass research and development for accomplishing the following set of subtasks.

a. Derive the isolines of a contour corresponding to 3D imagery by forming the convex hulls from the DTED posts with equal elevations.

b. Create an interface to morph 2D contours to fully featured 3D topography (and vice-versa) in graduated steps with a greater percentage of the height at each DTED post being displayed in each successive step (and vice-versa).

2. Design and implement the algorithms to detect ridges and crevasses using candidate methods such as high arc-to-chord ratios and highlight them upon demand to serve as patterns to aid user recognition and awareness of their environment.

3. Implement the methods to create either omni-directional or directional lighting. Also create an interface to assign the aforementioned source of light to any desired entity to obtain the line of sight to the assigned entities from the surrounding area.

4. Implement and apply suitable algorithms such as those by Dijkstra and Floyd to a graph on the vertex set comprised of the DTED posts and the edge set comprised of pairs of posts with a cost associated with each pair. Research suitable parameters to describe inter-post cost such as difference in terrain elevation between posts, soil composition at each post, and the traversing entity type.

5. Create suitable models of posts and protractors that can be overlaid upon the images generated by the AAcuity® PC-IG to enable the trainee to visualize distance and dispersion respectively. These models are created by using 3DsMax – a model generation tool – and their position and orientation controlled using NEXWARS.

6. Create heuristics using input from subject matter experts to gauge the threat level posed by an entity. This level will be a function of variably weighted parameters that include the size and blast radius of the munitions at the disposal of the entity, its distance to the observer and finally, its aspect and velocity with respect to the observer.

7. Embed Bayesian modeling methods into either the AAcuity® PC-IG or NEXWARS to enable the visualization system to estimate the likely trajectory and position of entities in the future. The model naturally requires a sufficient span of time in which to gather the amount of data (on any entity) required to make reasonably "informed" projections. The advantage in embedding this model into NEXWARS would be the reduction of computational load on the AAcuity® PC-IG which is very desirable since its primary task of high-end graphics rendering is inherently computationally intensive. On the other hand, the advantage in embedding this model into AAcuity® PC-IG would be the reduction of network traffic that would be otherwise experienced when transferring updated trajectories from NEXWARS to the AAcuity® PC-IG for display.

8. Create particle effect systems for generating dust clouds that are functionally accurate with respect to physical parameters such as soil composition and the nature of the tread of the entity generating dust. Similarly the particle systems must be capable of generating smoke that is functionally accurate with respect to physical parameters such as wind speed and the volume of smoke being generated by the corresponding entity.

9. Create the methods to compute the center of gravity of any desired set of entities and to assign and re-allocate entities to various partitions where each partition is representative of a formation. Create the cost function using which the entities with the highest cost are re-allocated to partitions.

10. Using a phased approach, build a prototype that incorporates all the visualization training methods and processes. Prototype development will evolve based upon iterative experimentation by the developers and corporate subject matter experts.

11. Perform a final assessment of the prototype using corporate, and government (if available) subject matter experts to refine the final prototype design in preparation for Phase III commercialization.

12. Provide a final report that encapsulates all Phase II research and formulates Phase III commercialization plans.

Phase II Visualization Training System Architecture

The prospective techniques and solutions generated during Phase I research for use in designing an effective system facilitating visualization training may be assimilated into a distributed architecture whose basic form is illustrated in Figure 33. Each module in the distributed architecture is comprised of two key components – the NEXWARS controller and the AAcuity® PC-IG. Each component resides on a separate physical system to attain enhanced system performance by virtue of the greater cumulative central processing unit (CPU) bandwidth afforded by two systems. Figure 33 illustrates four separate systems each of which is built atop the existing infrastructure of SDS products. The first is the AAcuity® PC-IG that currently serves as the backbone for all visual rendering and will be enhanced to provide the specific visualization images required to train a corresponding skill. The second is the NEXWARS controller that currently serves as a management tool for all exercises. This tool shall be enhanced to provide the functional control required to administer and control each training process.

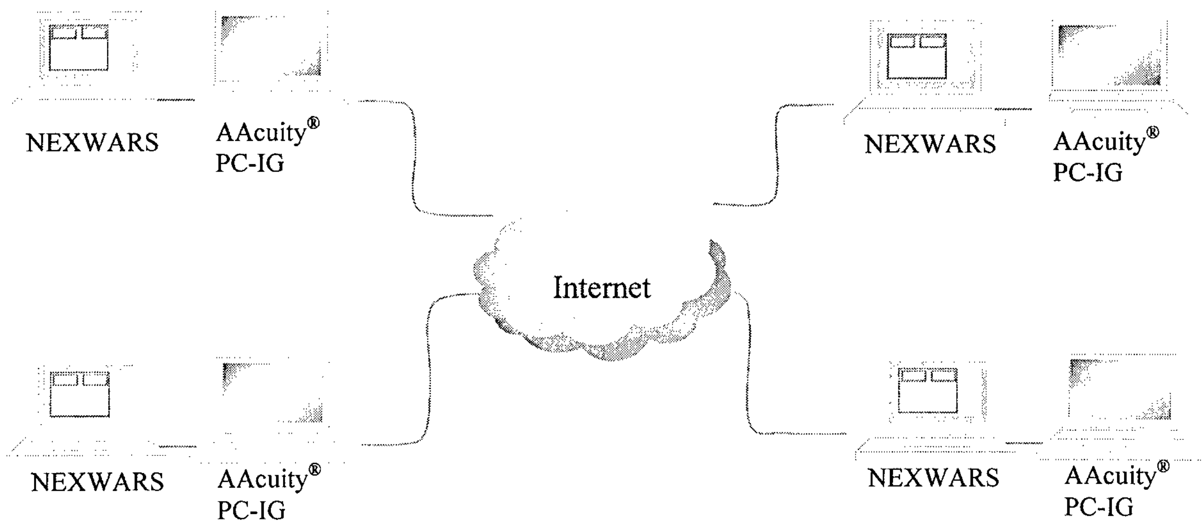

Figure 33. Architecture of the visualization training system.

The architecture shown in the illustration is fully scalable to an arbitrary number of systems over any communication infrastructure supporting the creation of Virtual Private Networks (VPN) and Transmission Control Protocol (TCP) sockets. Note that, the architecture displays a pair of laptops comprising each module. While this is not a required feature of the architecture, it is nevertheless a desirable one. It serves to reduce the physical size and number of system components enabling the system to be physically ported from one facility to another, deployed and substituted with relative ease. Also note that, a pair of physical systems is needed at each module for two reasons. The first is, the AAcuity® PC-IG requires the entire screen space on a display to render a virtual environment, and therefore prevents the NEXWARS controller from being displayed concurrently. The second is, the AAcuity® PC-IG is a computationally intensive application that is ideally run on a system that experiences the least amount of preemptions from other tasks. Both systems are connected to the Internet through a common Ethernet hub.

Phase II Visualization Training System Components

Note that the training processes themselves (treated as a component) are expected to be embedded within NEXWARS such that training control and feedback are maximized. For example, if a user incorrectly responds to a question in a given trial or session then the logical branch to decrease the level of difficulty or alter the viewpoint may be decided automatically. However, this fact does not obviate the need for human instructors or subject matter experts for they can make the most educated judgments about control and feedback. For this reason, NEXWARS may provide manual control which a trainer may use to override the automated training processes or simply control the entire process across all iterations.

Phase III Transitional Plan

One of SDS International's core business areas involves finding new products and helping transition those products from civilian to military applications/markets and vice-versa. As a company with an extensive operational military background, we have extensive ties throughout the military community (both with the U.S. and throughout many foreign countries), and SDS will capitalize upon those ties when developing its commercialization (Phase II Transition) strategy.

Based upon successes on our first awarded Small Business Innovative Research (SBIR) Phase II, we would expect to attract investments from—or sales to—both military and civilian sources early in Phase II, particularly, if the prototype system, sample training applications/scenarios and architecture readily support development/adaptation of similar systems for other applications.

While the immediate Phase III focus will be on Army applications, SDS envisions, and will pursue, similar training needs/opportunities within the other Services first, followed by civilian applications/opportunities. For example, recent SDS research efforts during an Office of the Secretary of Defense (OSD) sponsored SBIR Phase II focused upon training decision-making skills using low-cost PC-based systems in a distributed environment. Basic map reading is not only a cornerstone of successful Forward Observer (FO) training/performance within the US

Marine Corps, but also is essential to successful ground-based Forward Air Control (G-FAC) training. This is particularly true since G-FACs within the USAF are now composed of low-experience, non-pilot personnel.

Although the training applications described in this report are focused upon personnel who's primary duty is ground-force related, they can also cross the boundary to those who's primary focus is flight related. All military flight personnel must also learn to map read but from a flight and ground perspective. One of the more difficult tasks for flight-trained personnel is reading maps from a ground perspective—as is required of them during survival training (and in combat if shot down). As such, survival-training courses, particularly for aviators, could also benefit from this technology.

There are numerous similarities between military and commercial (non-military) visualization training requirements. Often, in an effort to take advantage of the investments made by the military, the commercial enterprises take advantage of those similarities by adopting military applications for their use. Similarly, there are significant opportunities to apply the proposed training system to a wide number of commercial business areas. Some of these areas are stated below.

- Any commercial endeavor that requires familiarity with terrain, personnel distribution and their interactions (ground-to ground, air-to-ground, ground-to-air, and air-to-air). Typical examples include civilian fire fighting teams (including personnel, ground vehicles and aircraft components) faced with fighting rapidly spreading forest fire.
- Coordination and planning by distributed engineering teams for the layout and construction of oil pipelines and the integration of supporting equipment traversing over substantial distances of terrain.
- Coordination and planning by multiple contracting teams towards urban development involving the construction of multi-lane roads, bridges, power infrastructure, and buildings on areas spanning hundreds of square miles.

In each of the aforementioned examples, the capabilities that are anticipated to be provided by the proposed training system to visualize terrain in real-time is indispensable to effective planning.

Summary

In this report, SDS has identified ten salient visualization skills critical to the success of warfighters at various levels of command on the battlefield by evaluating numerous battlefield scenarios with input from subject matter experts. These skills constitute a sizeable set of the cognitive and analytical capabilities required by warfighters to appreciate the battlefield dynamics of mission, enemy, terrain, troops and time across a broad spectrum of holistic scenarios. Therefore, SDS envisions the proposed training systems to incorporate a representative subset of these skills to maximize the spectrum of skills to which a subject training on this system is exposed.

SDS already possesses a proven suite of internally developed image generation technologies that can be leveraged to form the backbone of the proposed high-fidelity visualization tool. Furthermore, SDS also possesses a number of simulation management tools that are fully interoperable with those image generation tools. Using these as foundations, this report has outlined a number of technologies that may be developed and integrated into the existing image generation and management infrastructure to create the visualization training system. The proposed methods and the platform on which they are anticipated to be developed are technically and economically viable and deployable on the field with minimal support.

Finally, SDS in conjunction with Tuskegee University has proposed the outline of processes to train each of the identified visualization skills. These iterative processes are designed to provide feedback that may be used to refine successive iterations to match the skill-level of the user and provide a smooth learning curve. These processes are anticipated to yield results that are objective, accurate and can potentially demonstrate enhancements in the visualization skills of warfighters in the contemporary operating environment.

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